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A Maturity Assessment Model for Digital Twin-Value Stream Technology in Greenhouses

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for Digital Twin-Value Stream Technology in Greenhouses

By

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for Digital Twin-Value Stream Technology in Greenhouses

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ABSTRACT

With the rise in the global population, Greenhouse farming (GF) can help the agriculture sector by enabling year-round plant production regardless of location, climate, and other environmental factors. However, this will be realized when they can properly manage their production processes and limited resources. The lack of accurate and sufficient data is a significant barrier to traditional GF, and growers make daily decisions based on expenses rather than actual needs. A Digital Twin at their value stream level (DT-VS) is an emerging technology that can benefit this industry by giving decision-makers more precise insight into their business. However, to employ such technology in Greenhouses, understanding where they stand is a prerequisite for deciding future actions.

This thesis presents a method called "A Maturity Assessment Model for Digital Twin-Value Stream Technology in Greenhouses" to help greenhouse farmers manage their production processes and limited resources more effectively using digital twin technology. The model includes a questionnaire, numerical equations, and an assessment procedure to guide farmers in finding gaps and developing a strategic roadmap to transition from traditional greenhouse management to real-time monitoring and intelligent decision-making.

The proposed model has been validated through multiple use cases and case studies, with greenhouse participants reporting that implementing more cutting-edge technology can significantly accelerate their progress toward their business goals. According to the data analysis, 60% think that their current technology ecosystem helps them achieve their business goals, and 70% believe that implementing more cutting-edge technology than they currently use can greatly accelerate their progress toward those goals.

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LIST OF ABBREVIATIONS/SYMBOLS

ACPS: Agriculture Cyber-Physical System

AI: Artificial Intelligence

CDT: Cognitive Digital Twins

CPS: Cyber-Physical Systems

DT: Digital Twins

DT-VSM: Digital Twin-Value Stream Map

DVST: Digital Value Stream Twin

GDP: Gross Domestic Product

GF: Greenhouse Farming

IoT: Internet of Things

IPM: Integrated Pest Management

MM: Maturity Assessment Model

PLM: Product Lifecycle Management

PPC: Production Planning and Control Processes

RFID: Radio Frequency Identification

RT-DSM: Real-time scheduling and dispatching module

SMEs: Subject Matter Experts

SOP: Standard Operating Procedure

VSM: Value Stream Mapping

CHAPTER 1- INTRODUCTION

1.1. Research Motivation

One of the major global concerns is how to guarantee food security for the world's expanding population while maintaining long-term sustainable development. The issue of food security, sustainability, productivity, and profitability has become more crucial due to the growth in the global population and the market's demand for products with better standards of quality and maximum quantity.

A country's agriculture sector is essential since it raises animals and plants for food, medicinal herbs, and other products that support and enhance life. Agriculture and agri-food are also among the industries in Canada with the highest growth potential. This industry is now experiencing severe pressure due to the expanding global population.

Knowing how to utilize Greenhouses to produce plants is crucial, especially in areas with a lot of rain and places where the climate is always harsh, like Canada. Year-round plant production is one of the Greenhouse's main objectives regardless of location, temperature, and other environmental conditions. Unlike growing vegetables outdoors, sheltered agriculture frequently produces better-quality food, uses resources like nutrients, water, and crop protection agents better, and is less dependent on weather.

Plant production, which is the main form of production in agriculture, may be impacted by natural disasters and other unfavorable events. Currently, pest management methods rely on manual management techniques to identify regions with high pest populations, and pest identification is constrained by the prolonged sampling time. Data gathering is frequently insufficient and incurs considerable administration expense. Additionally, in farming, operational decisions are often taken without taking the value stream's implications into account in favor of cost savings.

Giving management more accurate information makes it easier to find problems and flaws, reduces errors, streamlines the process, and allows for continual improvement. Real-time data collection and analysis combined with modern visualization approaches, made possible by Digital Twin-Value Stream, can contribute to increased process transparency and optimization, affect people's behavior, enable intelligent decision-making, and better documentation and communication. Digital transformation demands a new organizational model and changes in physical infrastructure, operations and technology, human resources, and practices management.

Smaller businesses may find this structural transformation challenging, and it's possible that medium or large businesses won't start the digitalization process because of concern that they will only have some technical elements. To facilitate the transition to digitization, businesses must develop an appropriate roadmap that helps them identify, plan, and schedule each movement and decision they must make. Maturity Assessment Models are frequently used as a conceptual and measurement tool for maturity evaluation of organization capability, process efficiency, technology adoption level, etc. They capture the starting point of the improvement process and assist businesses in developing a strategic roadmap for process optimization or technology adoption to reach their desired state. These models are sometimes referred to as readiness models.

A significant barrier to DT-VS development in Greenhouse agriculture is the absence of a sector-specific guideline that facilitates the transition toward digitalization.

1.2. Statement of Engineering Problem

- To make everyday management decisions, greenhouses need more appropriate information.
- Traditionally, pest control and management decisions are solely cost-based, ignoring important factors.
- Advanced data-based decision-making support tools, such as Value Stream Mapping and Digital Twin Simulations, are needed.
- Transition from traditional Greenhouse management to advanced data-based decision-making needs a good platform and technologies.
- Tools like the maturity assessment model may be beneficial for successfully determining the Greenhouse's current state, its ability, and readiness toward developing a DT-VS and generating a realization plan to reach the desired state.
- There are several industry-specific maturity assessment models. However, there is a need to fill the gap for a maturity assessment model that can help enhance Greenhouse production using Digital Twin and Value Stream Mapping in Greenhouse agriculture.

1.3. Research Questions

- How can Digital Twin-Value Stream help Canadian growers in Greenhouse agriculture?
- How can growers evaluate whether their Greenhouse is capable or mature enough to employ the Digital Twin-Value Stream?

1.4. Research Objectives

This study intends to 1) Use a thorough literature review to demonstrate the significance of DT-VS in Greenhouse farming in response to the first research question; 2) Develop an industry-specific maturity assessment model for Greenhouses to guide farmers in identifying gaps and developing a strategic roadmap to transition from traditional greenhouse management to real-time monitoring and intelligent decision-making. Also, validate the proposed Model by using it in an actual case study to gauge its maturity. This will help growers evaluate their readiness and capability for DT-VS implementation.

1.5. Research Significant

Most papers about technology adoption in Greenhouse agriculture relate to environmental parameters like temperature, humidity, CO2, irrigation, etc. By establishing a sector-specific questionnaire, this study distinguishes itself from previous ones by focusing on Greenhouse agriculture processes and how technology adoption might help them.

Another advantage of this study is that it enables Greenhouses to evaluate the current maturity level of their processes and to compare their outcomes to those of other Greenhouses. Businesses typically dislike disclosing their state to outside parties. However, the study's questionnaire encourages Greenhouse involvement because of its anonymity aspect. Additionally, through the conversation with them, they learned about other prospects for process improvement that they needed to be made aware of, including Digital Twin, Industry 4.0, and Lean manufacturing principles and their capabilities.

1.6. Scope of Research

The scope of this research is evaluating Greenhouse agriculture processes located in the southern Canadian agriculture sectors of Windsor and Limington.

1.7. Research Hypothesis

The research Hypothesis of this thesis could be formulated as the following:

A maturity assessment model designed explicitly for greenhouse agriculture may be beneficial in identifying gaps between the current state and the desired state for establishing a DT-VS and developing a strategic roadmap to close the gap and transition from traditional greenhouse management to a smart lean Greenhouse by adopting value stream mapping and digital twin for advanced Greenhouse process management.

1.8. Research Tools

This study used a systematic design approach to develop the specific Maturity Assessment Model that can assist in developing a digital twin at the value stream level in Greenhouses. This study developed IDEF0 to comprehend its path better and illustrates the parameters that must be addressed to enable maturity assessment model development to satisfy the research objectives. In the end, specific use cases and case studies will be used in this study to validate the established idea.

1.9. Thesis Structure

This thesis breaks down into five chapters. The motivation and objective of the research, the statement of the engineering problem, the research questions, the hypotheses, and the scope of the study are all covered in the first chapter. The research's theoretical foundations and the knowledge gap that needs to be addressed are presented in Chapter 2. Processes and strategies for idea development are discussed in Chapter 3 along with the proposed model, developed questionnaire, numerical equations to quantify the results for better analysis, and an assessment procedure to guide growers from the start point to reach a realization plan for DT-VS employment. In chapter 4, multiple use cases and a case study were conducted to validate the proposed model. This chapter discusses the maturity assessment analysis and results and provides an implementation strategy. Finally, the most significant research contributions and conclusions will be discussed and summarized in chapter 5, along with recommendations for potential future studies.

CHAPTER 2- LITERATURE REVIEW

Because the topic has various facets that need to be examined, this preliminary literature study will use a theoretical approach.

2.1. Agricultural Industry

Agriculture is a vital industry in a country that cultivates animals and plants to provide food, fiber, medicinal herbs, and other products to sustain and improve life. Because of the world's rising population, this industry is currently under significant stress (Fei Tao, Meng Zhang and A.Y.C. Nee, 2019). The term "agricultural industry" refers to everything cultivated or raised for human consumption and encompasses, but is not limited to, industrial activities such as processing, cleaning, packaging, or storing the products of agricultural production. It excludes the manufacturing of processed foods derived from agricultural production or abattoirs. Performing farm, nursery, or Greenhouse tasks is considered primary agriculture. All businesses involved in the agriculture sector are referred to as agribusinesses. This covers not just farms but also the businesses that create, distribute, and maintain agricultural machinery and provide raw materials like seeds and the products that keep a farm in good health.

One of the sectors with the most significant potential for economic growth in Canada is agriculture and agri-food. Up to 544,600 people were employed countrywide in 2021 by the primary agriculture and food and beverage processing sectors, which generated 3.3% of Canada's GDP. With $31.9 billion or 1.6 percent of the country's GDP, Canadian primary agriculture is a major economic engine that is geographically widespread across the country (Anonym, 2022):

- 189,874 farms.
- farms cover 62.2 million hectares or 6.3% of Canada's land area.
- concentrated across the Prairies, Quebec, and Southern Ontario.
- average farm size doubled over the last 50 years due to increased consolidation and technological advances.

One of the leading global challenges is ensuring food security for the world's growing population while maintaining long-term sustainable development. According to the Food and Agriculture Organization, agricultural and food production will need to grow to feed the world population, reaching around 10 billion by 2050. Due to the increase in world population and market demand for higher product quantity and quality standards, the issues of food security, sustainability, productivity, and profitability have become more critical (Nasirahmadi and Hensel, 2022).

Greenhouse farming is known as the agricultural method of growing crops under protected buildings coated in a transparent, or partially transparent, material, such as glasshouses, shade houses, or screen houses. This method of utilizing Greenhouses to grow plants is essential, especially in regions with considerable rainfall and locations where the climate is always on the extreme side. One of a Greenhouse's primary goals is to enable year-round plant production regardless of location, weather, and other environmental factors. Unlike outdoor vegetable production, sheltered agriculture often yields higher-quality produce and uses water, nutrients, and crop protection chemicals more efficiently. Additionally, sheltered agriculture guarantees timely product delivery and is less reliant on climatic conditions. The major drawback of Greenhouse farming is primarily monetary in nature. Farmers only need the money for seed, labor, and any additional expenditures related to equipment or land when they plant outside. Greenhouse farming adds a new set of costs for structures and their upkeep. Costs are typically significantly higher for farmers who need to heat their Greenhouses' interiors artificially.

Natural disasters and other undesirable occurrences might affect plant production, which is the primary production in agriculture. Numerous pests, such as bacteria, fungi, weeds, and insects, hurt agriculture, resulting in lower productivity and poor product quality.

IPM, or Integrated Pest Management, is a decision-making process for controlling pests while protecting the environment and relies on a combination of common-sense practices. The life cycles of pests and how they interact with the environment are studied in detail and up to date in IPM programs. This information, in conjunction with available pest control methods, is used to manage pest damage by the most economical means and with the least possible hazard to people, property, and the environment. Techniques employed in the Integrated Pest Management system span from preventative and cultural strategies to biological, physical, behavioral, and chemical controls. A management solution for a specific pest or the entire pest complex comprising insects, mites, diseases, and weeds impacting a particular crop may include one or more methods (Anonym, no date). The following covers the six components of an Integrated Pest Management program as well as the difficulties associated with traditional IPM:

1. **Prevention:** When pest problems are avoided, pests are not present to cause harm; hence no pest control methods are required. Pruning is one of the preventive actions in Greenhouses, which is the selective removal of certain parts of a plant, such as branches, buds, or roots. The process comprises the purposeful removal of sick, damaged, dead, non-productive, structurally unsound, or otherwise undesired plant material from the crop, allowing for fresh growth while protecting your property and passers-by and enabling light and air to reach the center of the bush. It can affect the plant’s size and shape, quality and quantity of fruit, prevent insect infestation, and enhance the plant's natural structure and healthy growth.
2. **Identification:** When a potential pest problem occurs, the pest must be recognized accurately. This is crucial since most pest control treatments are pest specific. Once the pest has been identified, research its behavior and life cycle. This helps determine when to intervene and what methods to employ to limit the number of pests. And to avoid this happening again, do a root cause analysis.
3. **Monitoring:** Always watch for pest populations, beneficial species, and environmental conditions that cause problems. Monitoring is vital because it gives the information needed to promptly make judgments regarding the treatment time, placement, and needs. Regular inspections for pests or evidence of their presence are part of the monitoring program. Monitoring for natural enemies of pests is also essential since they can assist in controlling pest populations. Visual inspections (insects, illnesses, weeds) and/or counts of insects trapped in traps are employed to assess pest populations for particular pests.
4. **Action Threshold:** The level of pest population at which action is required is known as the action threshold. Each insect and crop combination will have a distinct control. It depends on 1) What extent of damage is acceptable, 2). which parts of the plant are impacted, and 3) The cost of the treatments.
5. **Management Options:** Over the years, chemical pesticides have significantly contributed to the fight against pests and diseases. Aside from the fact that agrochemicals have considerably increased agricultural output, they have adversely affected soil health, water quality, and product quality. They have caused problems such as insect resistance, plant genetic variety, and harmful residues in food and feed. Besides, reliance on chemical pesticides and their excessive usage has several adverse environmental consequences. Based on (Leng *et al.,* 2011) study, the financial cost of environmental and social economy loss is assessed to be $8.1 billion per year. Considering the negative impacts of agrochemicals, such as pesticide resistance, pest revival, secondary pest outbreaks, and

pesticide residues in produce, soil, air, and water, it is now critical to discover alternatives to this synthetic agriculture. The use of biofertilizers and biopesticides can help to address these issues in a responsible manner. Biopesticides are naturally occurring substances derived from living organisms (natural enemies) or their products (microbial products) or by-products (semi chemicals) that can control pests through nontoxic methods and cause fewer adverse effects on the ecosystem and human health and can therefore be used for pest management (Kumar and Singh, 2015). An IPM program may incorporate one or more management strategies/ solutions to target a specific pest or pests. and choosing the right combination of them relies on a variety of factors like the cost of the solution and the least possible hazard to people, property, and the environment.

6. **Evaluation:** It is critical to undertake follow-up monitoring or inspections to determine the efficacy of the IPM program. Keep track of what worked and what did not, and analyze the information to assist plan pest prevention and control operations.

Among the challenges of this method, the following can be stated. The technique, which does not use automatic recording technology, depends on manual measurement to pinpoint areas with high pest densities on a 10-day time scale with inadequate both temporal and geographic precision. It also does not give detailed information about infield variances. Data gathering is frequently insufficient and incurs considerable administration expenses. Furthermore, the extended sample period limits the system's ability to identify insect pest risks. The data cannot be used to simulate pest distribution in the crop or to examine the variables affecting a particular pest's population dynamics. Additionally, the program does not accurately time the delivery of warning signals regarding unexpected pest outbreaks (Jiang *et al.*, 2013). The traditional methods have been difficult to deal with fine-grained identification of pests, and their practical deployment is low (Ma *et al.*, 2021).

Canada has several advantages that can help it become a world leader in the production and processing of food, including a wealth of natural resources, including land and water; access to markets abroad; excellent capabilities for research and development; and a solid international reputation as a reliable source of high-quality, safe food.

The industry will continue to be competitive, sustainable, resilient, and profitable if it takes advantage of important opportunities like digitization and the use of smart technology.

2.2. Value Stream Mapping: A Lean Manufacturing System Tool

Manufacturers encounter cost-cutting and efficiency concerns in their operations. To thrive in today's highly competitive market, they must develop ways to minimize manufacturing time and prices, increase operating performance and product quality, and achieve long-term success in the fight against Muda by identifying and eliminating all underlying wastes, resulting in increased value for customers.

Lean manufacturing principles determine the value of a product or service as perceived by the customer, then align the flow with that value, striving for perfection through continuous improvement to reduce waste. Value Stream Mapping (VSM), Cellular Manufacturing (CM), U-line system, Line Balancing, Inventory control, Single Minute Exchange of Dies (SMED), Pull System, Kanban, and Production Levelling are some common lean aspects that assist eliminate waste and maximize the product's value (Sundar, Balaji and Satheesh Kumar, 2014).

Anything that a customer is prepared to pay for–is considered "Value." Value Stream Mapping (VSM), a lean tool created by Rother and Shook , is used for visualization of the current state of the value stream of a business and detailed analysis of the production process to identify waste and allows for process improvements by developing the future state of the value stream to lower production costs, improve response time to satisfy customer demand, and produce higher quality products (Lie and Kusumastuti, 2021). VSM is the collection of steps, whether value-added or non-value-added; a business converts a finished product from raw material to the customer's hand to offer value to a client by minimizing non-value-added activities. (Sultan and Khodabandehloo, 2020) Stated in their thesis that the material flows through the value stream is the more obvious flow. However, information flow, which guides each process in determining what to produce or do next, is a further crucial flow. Information flow and material flow are treated as two sides of the same coin in lean production, which highlights their respective importance. VSM is the only qualitative tool that depicts material and information flows in a single diagram, figure1.

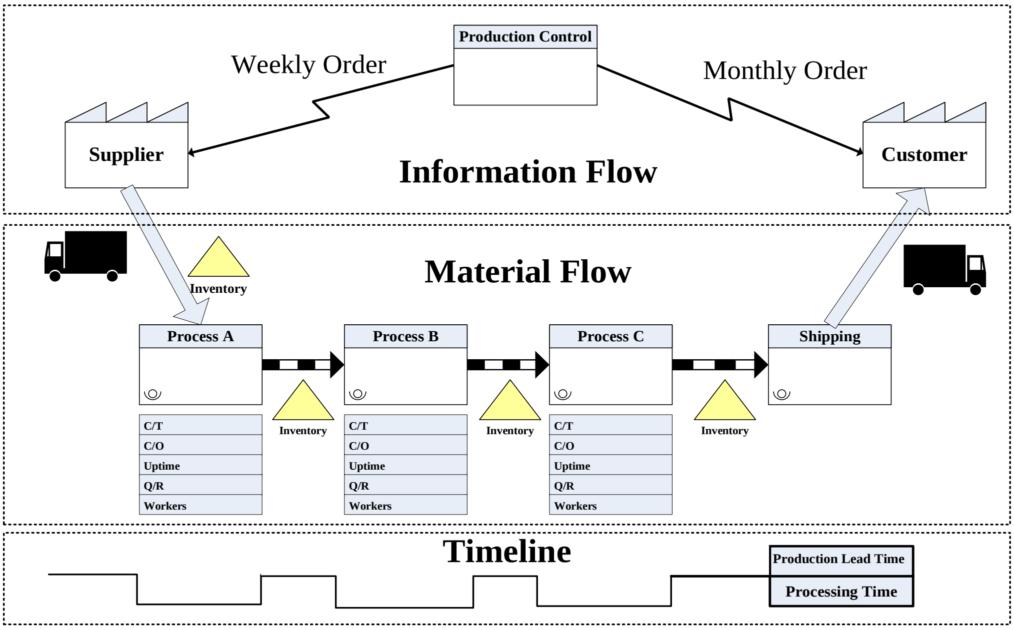

Figure 1: Value Stream Mapping (VSM) – Adapted from (Bucourt et al., *2011*)

Numerous studies have demonstrated various types of benefits from VSM implementations in the manufacturing industry in recent years like cost savings, increased productivity, a noticeable decrease in cycle time, bottleneck time, waiting time, material handling time, defects, and other non-value-added activities, and improved product quality (Saraswat *et al.*, 2014).

According to a recent literature review on the subject, there are several problems, challenges, and limits to VSM implementation, including the following: 1) Most people believe that creating a value stream map is a straightforward process that only requires a pen and paper, a few visits to the shop floor, collecting process data, and drawing the map on paper. However, accurately depicting the problems present in the process can be challenging; 2) VSM just represents the current state and operations as a snapshot. So, depending on the level of stock and other elements present when the process is mapped, it is either very pessimistic or very optimistic. Also, the VSM is developed using the average values of the aggregated data, which misrepresents the real world and misleads decision-makers. So, its static nature is a major drawback that prohibits the VSM from being implemented in a system with dynamic; 3) A lack of clarity in procedures and standardization, documentation, and, in particular, document revision management where processes have changed; 4) As technology becomes more advanced, there are issues/ difficulties in monitoring data in processes. Today's manufacturing processes generate a massive amount of data in wide and varied volumes, rates, and forms. Extracting input from multiple inputs and making real-time decisions is a substantial issue for current production systems; 5) Additionally, unconsidered information in the production environment will likely reveal helpful hints for waste or process issues and potential improvements that might be overlooked; 6) Sometimes, the VSM implementation procedure takes a lot of time. The systems must continue working with the issue after it has been identified and VSM has been analyzed until a workable solution has been found (Forno *et al.*, 2014; Sultan and Khodabandehloo, 2020; Abou Tabl, Alkhateeb and ElMaraghy, 2021).

There are opportunities to develop technologies to assist in measuring data to obtain current state maps. These technologies can improve data reliability and better decisions in defining future maps. Simulators have lately been employed in several studies to improve VSM by utilizing and assessing data in a dynamic context. (Pekarcíková *et al.*, 2021) Emphasize the significance of combining simple Lean Production tools with software to find, test, and develop alternative solutions for the demands of flexible reflection on changes in various parameters within the value stream. In the end, this study discusses the distinctions between VSM made traditionally, and VSM made with software support.

2.3. Digital Twin

The focus of traditional production methods is on production planning and control (PPC) procedures based on historical data analysis and expert experiences. As information technologies advance, new frameworks and methods are required to optimize the coordination and control of production processes by integrating real-time data sources like IoT data, improving traditional process planning methods such as value stream mapping, and developing digital twin-enabled data analysis and simulation techniques (Lu, Liu and Min, 2021).

Accurate data from the shop floor is becoming increasingly important to manufacturing companies because this information shows the current shop floor condition and is usually utilized to make managerial decisions. Digital Twins (DT) have emerged as a critical technology for modern design and production engineering workflows, driven by the need to reduce product development lead-time and improve product quality, and enabled by the vast development of smart sensors, the Internet of Things (IoT), cloud computing, machine learning, artificial intelligence (AI), information, and simulation technologies such as cyber-physical systems (CPS).

Among all literature reviews, NASA most likely came up with the original description of DT: “A Digital Twin is an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.” However, the International Academy for Production Engineering (CIRP) defines a Digital Twin as follows to bridge the gap between these broadly divergent understandings: “A Digital Twin is a digital representation of a unique active product (real device, object, machine, service or intangible asset) or unique product-service system (a system consisting of a product and a related service) that comprises its selected characteristics, properties, conditions and behaviors using models, information and data within a single or even across multiple lifecycle phases” (Dittrich *et al.*, 2020). This manufacturing concept allows manufacturers to develop fit-for-purpose digital representations of their production systems and processes utilizing real-time or near real-time data and information to enable analysis, decision-making, and control for a specific goal and scope (Shao and Helu, 2020).

Michael Grieves unofficially proposed the DT concept in 2003 during his presentation on product lifecycle management (PLM) with the title “Conceptual Ideal for PLM". The three primary components of Grieves' DT model are the significant elements in the DT three-dimension framework, as illustrated in figure 2: 1) A real space containing a physical object; 2) A virtual space containing a virtual object; 3) The link for data flow from real space to virtual space (and virtual sub-spaces) and information flow from virtual space (and sub-spaces) to real space. This final component facilitates data exchange, allowing virtual and physical systems to converge and synchronize (Barricelli, Casiraghi and Fogli, 2019).

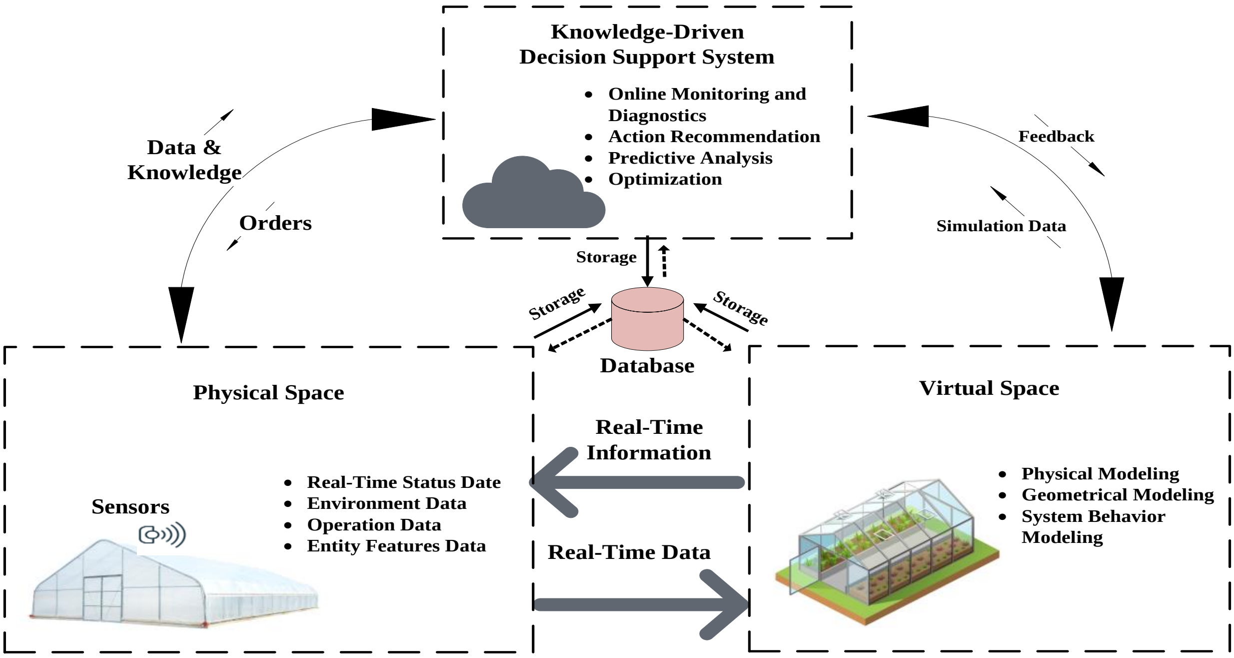

Figure 2: Digital Twin Development and Deployment adapted from (Assad Neto et al.*, 2020; Chaplin, Martinez-Arellano and Mazzoleni, 2020; Botín-Sanabria* et al.*, 2022; Guo and Lv, 2022)*

In this context, numerous understandings and definitions of a DT have been presented in industry and academia due to distinct application domains. (Qi *et al.*, 2021) Studied and summarized the most commonly utilized enabling technologies and tools for DT applications to provide technology and tool references for future DT applications. (Barricelli, Casiraghi and Fogli, 2019) Discussed the results of a study focused on the analysis of the state-of-the-art definitions of DT, the investigation of the main characteristics that a DT should possess, and the exploration of the domains in which DT applications are currently being developed. (Fei Tao, Meng Zhang and A.Y.C. Nee, 2019) Has presented an expanded five-dimension definition for the DT, including DT data and services and the three-dimensional version. In contrast to earlier models, the newly proposed description, in addition to the physical-virtual interaction, can fuse data from both the physical and virtual components employing DT data for more comprehensive and accurate information capture.

(Ghobakhloo, 2018) Stated that "the intelligent ERP, in conjunction with data mining procedures, would enable DT models that provide a digital representation of the past and current behavior of a single object up to the entire manufacturing system, the feature that can significantly contribute to the development of smart factory".

The research by (Tran *et al.*, 2021) discussed three layers of communication between digital and physical objects: As data is manually fed into the system at the initial level, the digital model is offline. The digital shadow model automatically gathers information from the shop floor at level two. Real-time data is effortlessly incorporated into the DT at the top level.

CPS and DTs both emphasize an effective cyber-physical connection, real-time communication, organizational integration, and in-depth cooperation as core principles. However, there are many aspects of CPS and DTs that are different, including their history, development, engineering methods, cyber-physical mapping, and fundamental components. (Tao *et al.*, 2019) In their study analyzed CPS and DTs from several perspectives, pointing out their similarities and differences as well as their relationships.

Most current publication introduced the idea of Cognitive Digital Twins (CDT), their characteristics, history, and application to assist humans in making better decisions and accomplishing goals and tasks that typically need human intellect, such as planning, thinking, and learning. (ElMaraghy and ElMaraghy, 2022) Stated that cognitive systems are able to mimic the functioning of the human brain by using self-learning algorithms that use data mining, pattern recognition, and language management. The "cognitive sensor networks" enable the real-time capture of production and process data as well as prompt feedback to the process control. Also, the automation of diagnostics by cognitive machine learning relies on algorithms that learn from data rather than exact programming. The shift from data to cognitive adaptation enables the cognitive system to analyze data from workflows, context, and the surrounding environment to improve manufacturing quality, maximize asset utilization, increase operations efficiency, improve decision-making, and increase cost savings throughout the factory value chain.

A DT is undeniably transformative not only in how we design and operate cyber-physical intelligent systems but also in how we advance the modularity of multi-disciplinary systems to address fundamental barriers that aren't addressed by current evolutionary modeling practices. As a result, the current challenges and enabling technologies of DT implementation, along with recommendations and reflections for various stakeholders, have been discovered and discussed in the (Rasheed, San and Kvamsdal, 2020) study, as well as a brief description of eight values that any DT is capable of generating based on an Oracle examination including 1) Real-time remote monitoring and control, 2) Predictive maintenance and scheduling, 3) More efficient and informed decision support system, 4) Better intra- and inter-team synergy and collaboration, 5) Better documentation and communication.

The results of the Scopus search illustrate that Digital Twinning is a significant and growing trend, figure 3, in many applications, figure 4. Evidence and graphs show that engineering and computer science account for the most articles (31.44% and 24.51%, respectively), whereas agricultural science accounts for 0.43%.

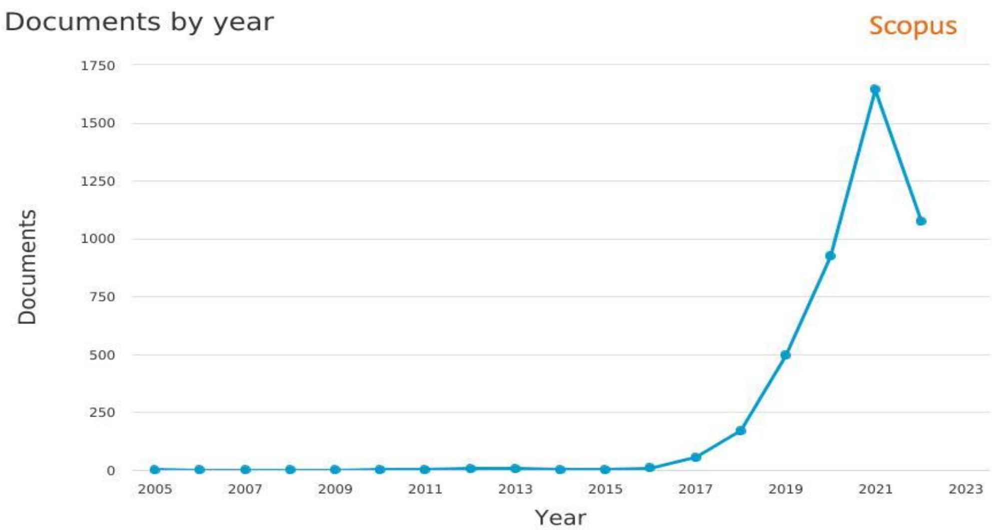

Figure 3: The growth in papers on "Digital Twin" as shown in Scopus from 2003-2022

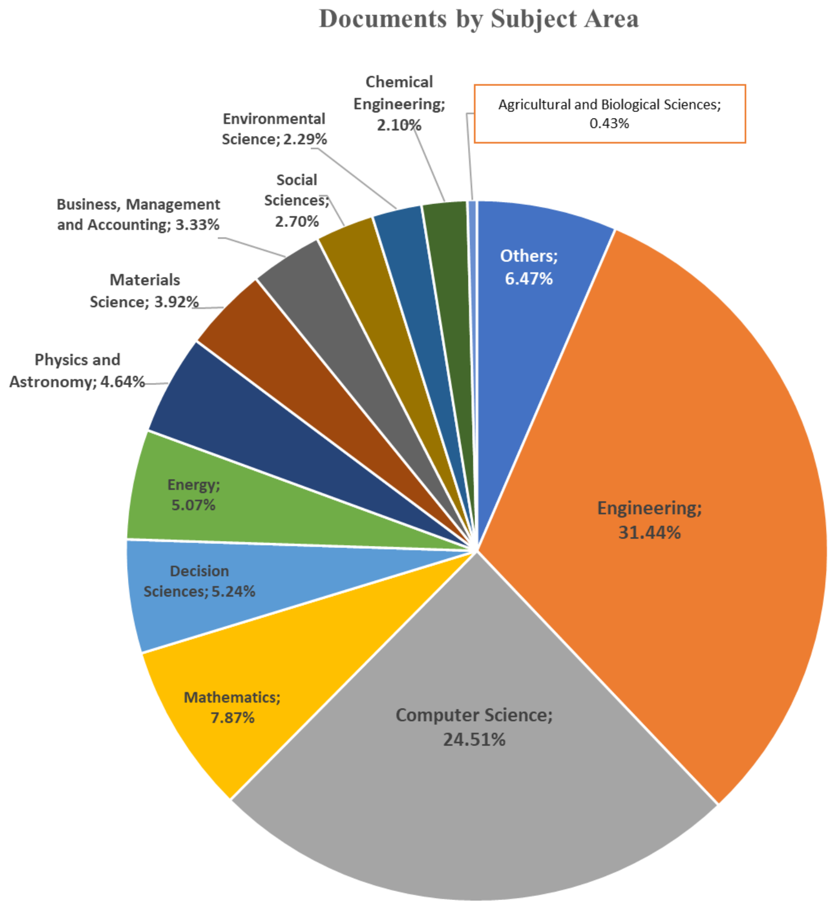

Figure 4: Application of the Digital Twin in various subjects from 2003-2022

2.4. Relationship between Value Stream Mapping and Digital Twin: DT-VSM

As previously said, Lean Manufacturing employs a variety of tools, each of which captures different types of data. As a result, using data analytics in process optimization is one of the most challenging parts of lean manufacturing, which can significantly impact the success rate of Lean adoption. Managers who lack the data/ information they need regarding decision-making, and are not aware of critical considerations and their potential effects, are less likely to recognize the strong influence of good practices on their company's performance.

To analyze and redesign value streams, VSM- a lean manufacturing tool, is frequently used in manufacturing. The objective is to enhance procedures, lessen waste, and establish a proper product flow. Despite its many advantages, VSM has drawbacks in today's dynamic production situations. It doesn't meet the criteria of offering trustworthy data for a practical Value Stream Design (VSD) followed by a targeted improvement plan. As a result, the VSM frequently involves uncertainty and depends on specialized knowledge (Frick and Metternich, 2022). To adapt the VSM to the present dynamics of production systems, further development is required. Initiative Industry 4.0 technologies- like IoT, RFID, Big Dara, RT-DSM, etc., enable lean tools to operate more dynamically, speeding up the information-sharing process and enhancing the decision-making of production managers and operators (Salvadorinho and Teixeira, 2021).

(Frick and Metternich, 2022) Offered the so-called Digital Value Stream Twin as a framework for implementing a DT at the value stream level (DVST). A thorough digital representation of a value stream is meant by the term "DVST". Through mathematical models and data, it captures the properties, surroundings, and behaviors of a value stream. Instead of improving a single manufacturing process, optimizing a value stream, as a whole, is the top goal of DVST. The target/ actual comparison between the current state and the given target state of the value stream design is the foundation of the DVST. Relevant data is automatically gathered, moved from the physical value stream to the digital representation, analyzed, and delivered to make this feasible. The system generates precise adaption ideas for improvement based on optimization algorithms, which are subsequently offered to the decision maker. The operational production management and value stream manager, depending on the type of decisions, still have the last say on whether to change the value stream and feed the information back into the physical value stream; the DVST only facilitates the decision-making process, and an employee must actively modify for a physical asset to be adjusted in the value stream.

(Lu, Liu and Min, 2021) Stated that traditional VSM methodologies are insufficient or impractical in undertaking production process redesigning and reengineering tasks due to restrictions in collecting reliable performance evaluations of the production line. They suggested a digital twin- enabled VSM method for SMEs by combining internet of things (IoT) technology and the Efficiency Validate Analysis (EVA) simulation framework to better determine the key indexes in the VSM analysis process. RFID devices are the primary source of IoT data used to develop the DT model in the mentioned study. It is recommended that in future studies, the structure and technique can be expanded in a way that more IoT data sources, such as vehicles, wearables, and position devices, will be included in the modeling DT. Modern visualization approaches, such as the DT, when used effectively, may increase manufacturing process transparency, affect people's behavior, enable continuous improvement, promote shared ownership, and give management more accurate information making it easier for them to identify issues and flaws, minimizes mistakes, streamlines the process, and enables them to spot ad hoc linkages. Everything will work together to boost the business's overall success (Holopainen *et al.*, 2021). However, it is essential to consider that using high automation technologies to increase production system flexibility may result in high investment costs, poor returns, and, ultimately, investment transformation failure (Salvadorinho and Teixeira, 2021).

In comparison between the DT and VSM, (Uhlemann *et al.*, 2017) outlined, “DT is near real-time linked simulation of the production system for continuous data acquisition while VSM is manual data acquisition conducted to get a snapshot of the current state.”, figure 5.

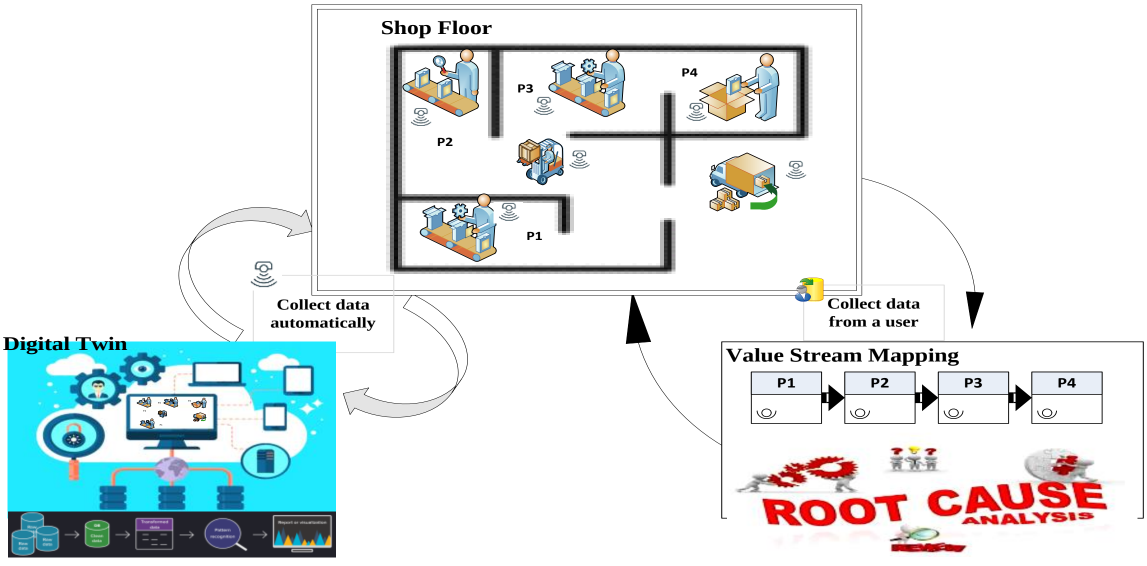

Figure 5: Comparison between the Digital Twin and Value Stream Mapping adapted from (Uhlemann et al., 2017)

The association between research keywords (Co-occurrence of keywords) based on 65 published papers from 2005 to 2022 is revealed in figure 6 by the bibliometric study to explore the relationship between the application of DT and VSM- a lean manufacturing tool. Additionally, the density of the lines and dots indicates greater study in a certain region. (TITLE-ABS-KEY (" digital twin" AND " VSM" OR " value stream" OR " value stream mapping " OR " lean" OR "digital twin-VSM" OR "DT-VSM” OR "VSM 4.0" OR "lean 4.0" OR "digital twin value stream" OR "cyber-physical lean" OR "cyber-physical value stream")). The result shows that many authors have discussed the relationship between these two concepts, the advantages of combining them, and their applications, such as optimization, reengineering, scheduling, etc., in their works. However, there is always the potential for improvement, especially concerning their application in sectors other than manufacturing.

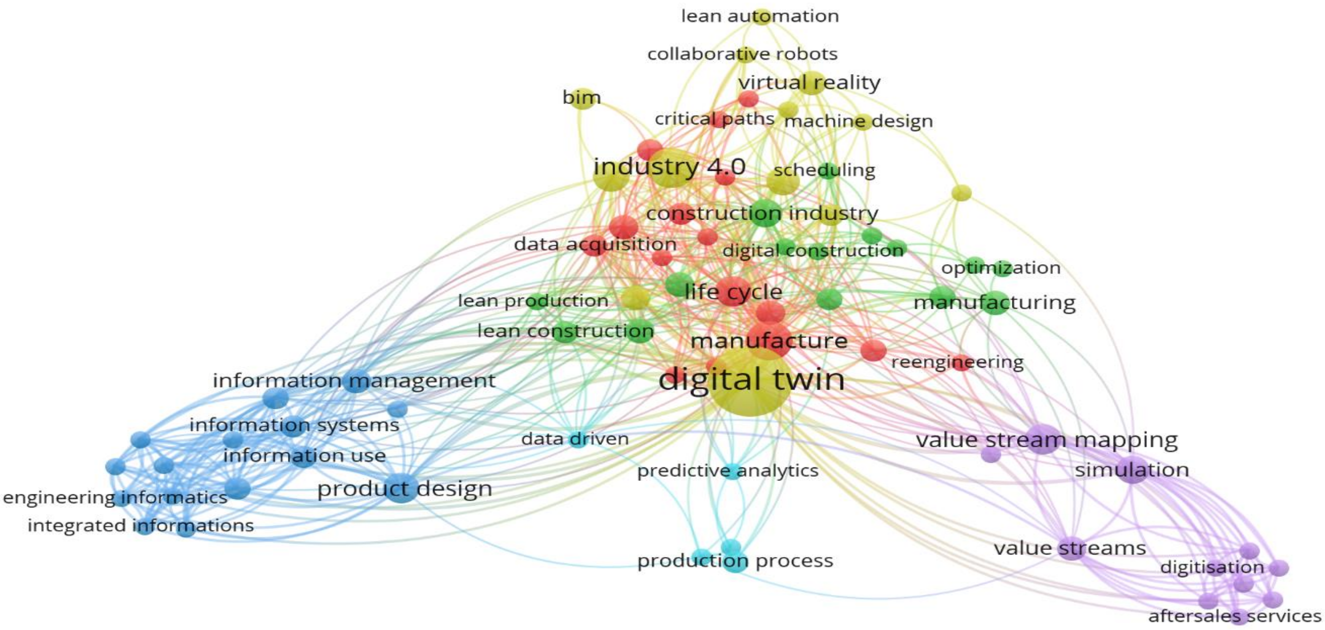

Figure 6: A bibliometric examination of the correlation between DT and VSM

2.5. Digital Twin-Value Stream application in Greenhouse Agriculture

The agriculture sector has a great opportunity to maximize efficiency by reducing waste and improving product quality by implementing lean concepts. In farming, operational choices are typically made based on costs without considering their effects on the value stream (Dora, Lambrecht, and Gellynck, 2015). They fail to consider the potentially lethal waste that occurs in agriculture. For instance, improper fertilizer usage, an improper feed mix, or poor seed quality might result in product failure. Long-distance biopesticide transportation might decrease its efficacy. Pests can grow in a crop by waiting for a particular activity or not doing it at the right moment, and growers ignore the value at risk due to pest infestation. Over-application of nutrients will flow off the fields, damage streams and groundwater, and drive-up fertilizer costs.

Even though adopting VSM and applying Lean thinking to the agriculture industry has several advantages to overcome the mentioned challenges, there have only been a few studies conducted in this field, figure 7 illustrates the pattern, and most of them are associated with the lean idea. There need to be more adequate practical studies about using VSM in agriculture, particularly Greenhouse agriculture.

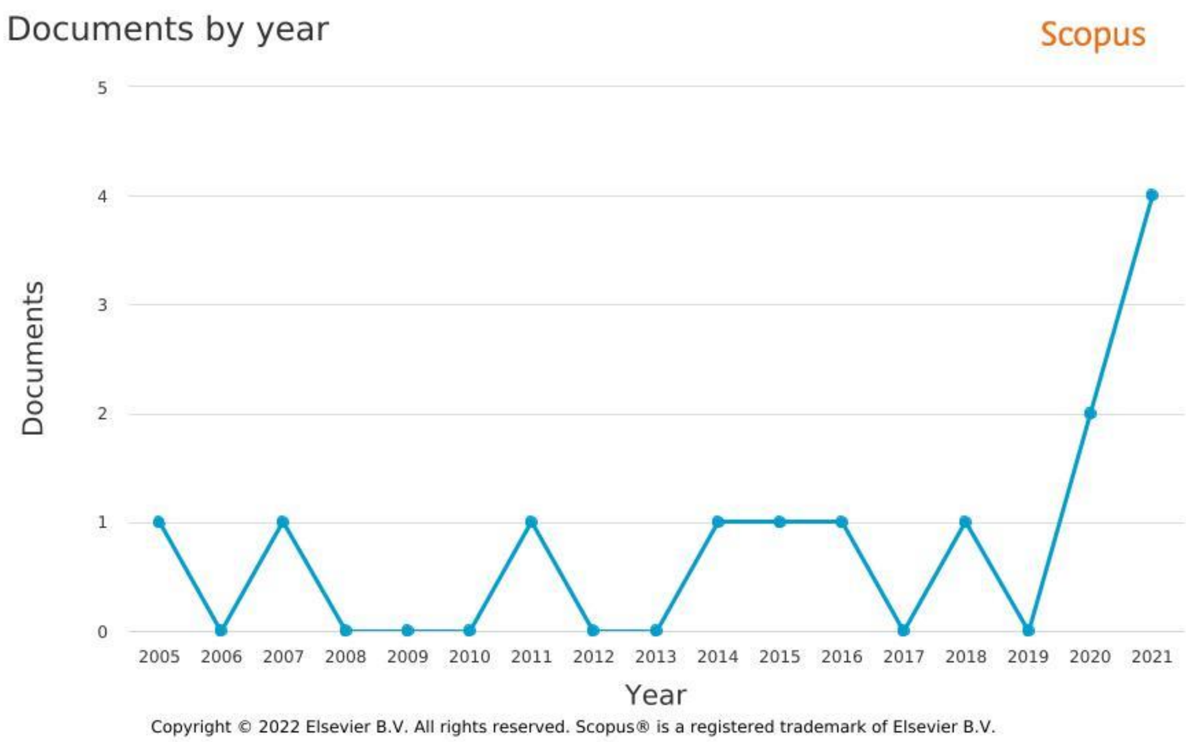

Figure 7: Lean Techniques in Agriculture Production publication trends

Although VSM provides many advantages for every industry, it has shortcomings, as was already discussed. Due to a lack of awareness about soil types, yields, crops, weather conditions, poor use of intrants, irrigation problems, and crop failures in the past, farmers were forced to make intuitive farm modifications (Coulibaly *et al.*, 2022). Agriculture and food production systems have been influenced by digitalization, which also makes it feasible to use technology and cutting-edge data processing methods in the agricultural sector. The goal of digital farming is to leverage information on farm assets to resolve several current issues with processes and resource management, climate protection, and food security. The use of digital strategies is anticipated to increase process optimization and decision-making support

(Nasirahmadi and Hensel, 2022). (Sun, Zhang and Chen, 2012) Developed the digital Greenhouse expert system based on their understanding of agricultural Greenhouse evolution, digital technology, and artificial intelligence technology, with the goal of enhancing crop management and promoting healthy crop growth.

Authors feel that the Digital Twin may serve as a primary way of agricultural management and has the potential to influence the agriculture industry and related businesses, including biopesticide application, farm supply chain, production, harvest, packaging and distribution, and sales and marketing (Fei Tao, Meng Zhang and A.Y.C. Nee, 2019). In Agriculture, A DT is a virtual representation of a farm that has the potential to increase production and efficiency while reducing waste and energy use (Nasirahmadi and Hensel, 2022). (Bhatia, Kumawat and Jaglan, 2022) Discussed the application of cyber-physical systems in agriculture (ACPS), including air, soil, fertilizer and irrigation monitoring, farm management system, etc., and how modern irrigation management techniques using agriculture-CPS models will reduce monetary losses due to over or under irrigation, movement of nutrients, pesticides, and chemicals into the water. They also stated that ACPS might be used primarily in two areas: environmental information acquisition and plant information (health of the crop and yield of the crop) collection. Greenhouses are quickly becoming high-tech industries and (Fatima *et al.*, 2023) stated, “this transformation is a result of the increased use of advanced sensors and control systems for climate management, irrigation, fertigation, lighting, crop monitoring, disease scouting, harvesting, internal transportation, sorting, and packaging.” They discussed in their study, the manual monitoring of the growing process is impossible in large Greenhouses. By employing digital information in (near), real-time, growers may now remotely monitor and control creative and data-driven greenhouse horticulture activities. They can monitor a detailed visual representation of the plants or machinery in the greenhouse from their workstation or smartphone, and they receive notifications for any potential problems. Digital twins in greenhouse horticulture can also assess previous conditions and predict future crop growth and harvests. On the digital representation, growers can simultaneously simulate corrective and preventive actions, and the farmer can then remotely apply the suggested remedies. The performance of the physical twin can be predicted using a digital twin, which integrates modelling, AI, and Big Data analytics with IoT and conventional sensor data from the production and cloud-based company data (Howard *et al.*, 2021). The Digital Twins assist in optimizing the production schedule, energy use, and labor costs by considering important variables such as production deadlines, quality grading, heating, artificial lighting, energy pricing (gas and electricity), and weather forecasts. In their study, (Pylianidis, Osinga and Athanasiadis, 2021), did a literature review of digital twin in agriculture and compared the findings with other disciplines. They reported DT have been discussed in various fields since 2011, but the first references to DT in agriculture happened in 2017. Figure 8 shows how the interest in DT in the agricultural industry is expanding quickly. As they discussed, It is more difficult to create DT for agricultural processes that involve living things like plants, animals, or food products than it is for human-made, non-living systems. The community needs to become knowledgeable on various related technologies, such as the Internet of Things, machine learning, and big data, to successfully develop DT. The majority of these technologies are currently being tested in new areas of agriculture, so it's possible that more DT will emerge at the prototype and deployed levels after the industry gains confidence in them and adopts best practices for their use. They listed the following as some of the advantages DT can offer to agriculture: personalized curation of complex systems, streamlining of operations, information fusion, uncertainty quantification, permission level controls, and human-centered intelligence. These could be obtained by employing DT widely and with various levels of functionality, like a DT for keeping track of environmental factors including CO2, humidity, and solar radiation, analyzing them in accordance with user-defined criteria, and reporting its findings. A DT of fields may utilize simulation to determine how it would behave in the specific settings where it will be used, before purchasing that equipment. A DT with learning capabilities would be able to identify trends in both historical and real-time environmental data that might help diseases start and spread. This would assist stakeholders in taking preventative action to stop the spread and emergence of diseases. The DT would also determine the key factors influencing these patterns, calculate associated risks, and express the uncertainties clearly, for instance by displaying probability metrics. A DT will be able to take into account the dynamics of water flow, fertilizer dispersion, and nutrient leaching between fields. It would offer variable fertilizer rates based on site-specific intelligence, such as how much can be absorbed by one farm without spreading to others, and how much should be irrigated into each field considering groundwater levels and the accessibility of irrigation infrastructure. The DT would continuously learn from past decisions made by the individual farmers in order to define the permissible levels of irrigation and fertilizer. (Knibbe *et al.*, 2022) Studied tomato crop digital twin in the Netherlands and reported its benefits and challenges, like a detailed model may be able to make accurate predictions, but it could also become a bottleneck if it becomes too complicated. “The model simulates relevant crop processes (light capture, photosynthesis, assimilate allocation, growth of leaf area and stem extension, yield), greenhouse climate dynamics (temperature, humidity, CO2), climate control measures (opening of windows, heating, CO2 injection, lighting, and screening), and crop handling (harvesting, leaf pruning).” They believed there were still many difficulties regarding the specification, accessibility, and reliability of pertinent data sources.

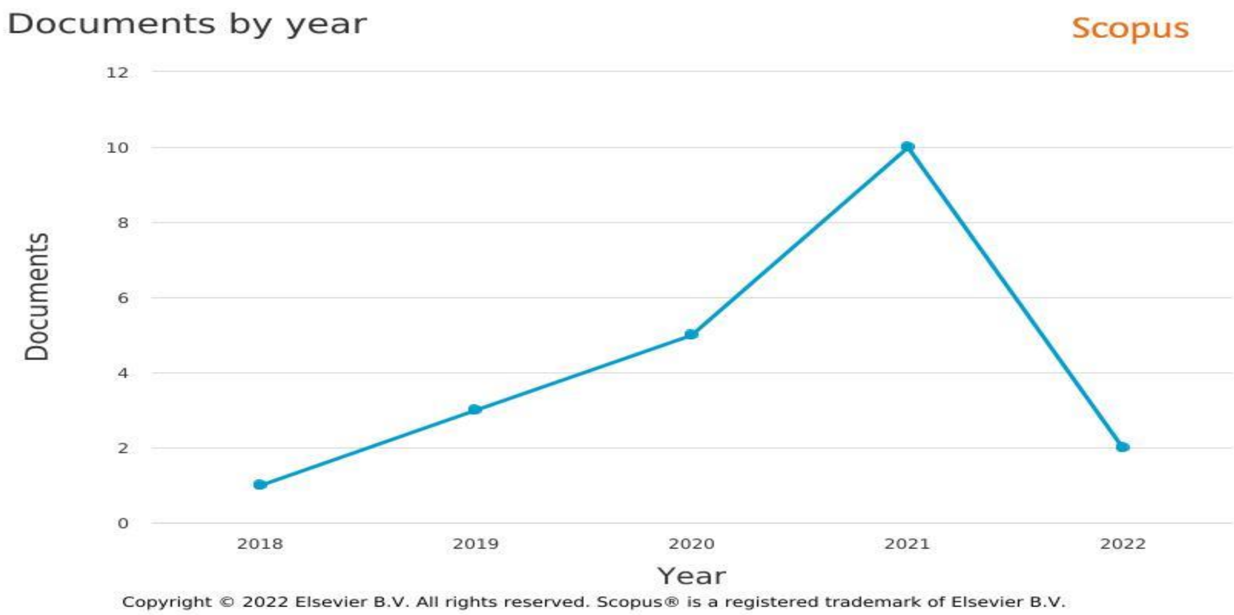

Figure 8: The growth in papers on "Digital Twin in Agriculture" as shown in Scopus.

A systematic literature survey and a bibliometric study were used to identify DT's current applications in the agriculture sector. The following key phrases and search terms from the databases of Scopus and Google Scholar were considered within article titles: "Digital Twin" AND "Agriculture" OR "farming" OR "Agricultural" OR "Cultivation" OR "Greenhouse farming" OR "Greenhouse Cultivation" OR "Greenhouse Agriculture" OR "Greenhouse Production" OR "Greenhouse Planting" OR “Greenhouse Horticulture.”

The findings reveal that, in comparison to the notable growth of research in the DT area in other industries, as illustrated in figure 4, and taking into account its numerous advantages and application, there have been comparatively few papers produced on the DT application in the agriculture sector, figure 8. The majority of the articles in this field also are related to automatic data collection using IoT and the application of AI & big data, figure 9. Even more DT-enabling technologies can help this industry increase productivity and quality, process optimization, and support growers in intelligent decision-making.

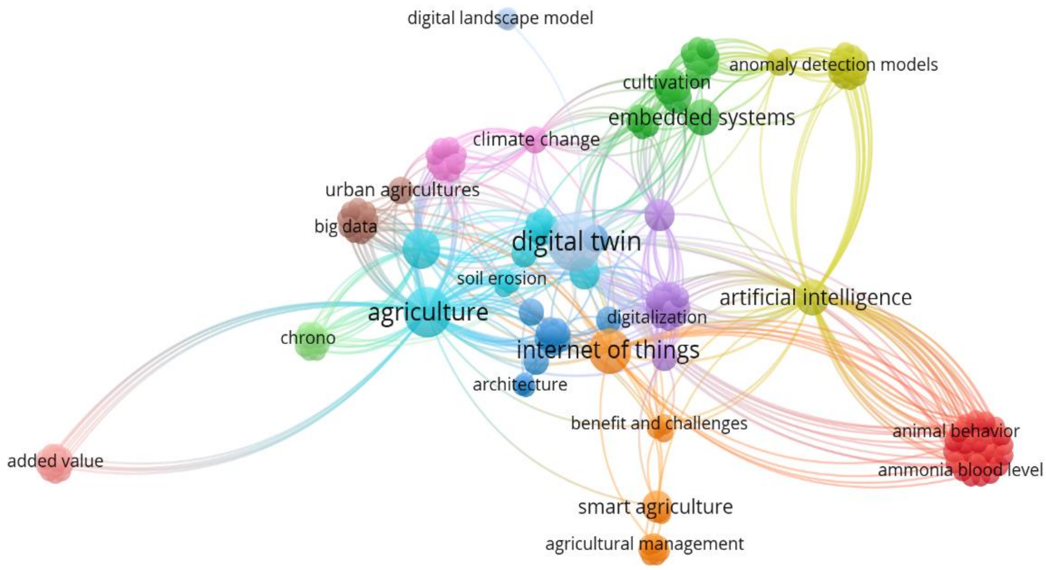

Figure 9: Bibliometric analysis of DT applications in agriculture

Besides that, most studies are focused on European nations, figure 11, so there need to be more studies on Canadian agriculture, especially Greenhouse agriculture. As previously indicated, one of the Canadian businesses with the most significant growth potential is the agricultural and agri-food industry. However, Canada's delicate and harsh environment makes the practice of growing food in Greenhouses very crucial.

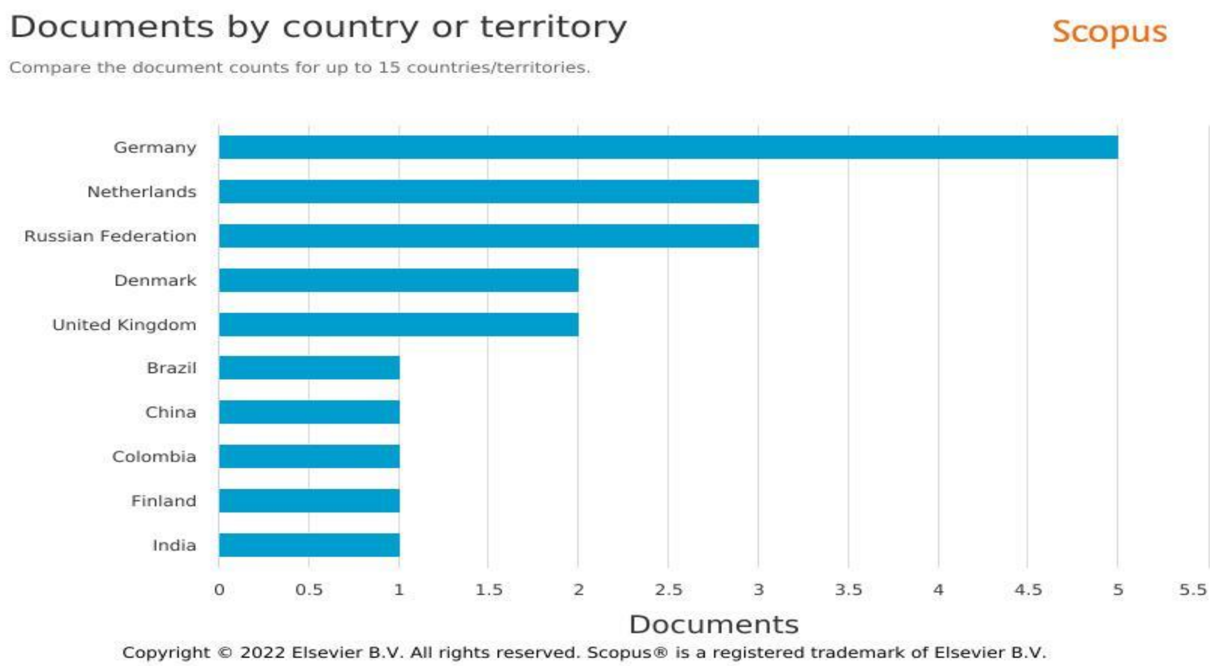

Figure 10: Different nations' studies on the application of DT in agriculture

A lot is happening simultaneously in Greenhouses. Every crop, every farm, and every season are different from one another and need a particular understanding of the biological, chemical, and physical processes occurring in plants and soils.

As previously stated, a wide variety of pests and insects can have a detrimental effect on agriculture by lowering productivity and affecting the quality of the products. IPM is a strategy to prevent or/or manage these kinds of disasters. This strategy's efficiency involves a thorough understanding of all standard operating procedures as well as expertise in how to carry them out appropriately, knowledge of various pest types, prevention methods, routine inspections for spotting pests or signs of their presence, and understanding of their life cycle and available treatments, and choose the best method to employ to get rid of it as quickly as possible.

The number of employees, level of knowledge and competence, and available funding are the limitations for every business, even though they all have several goals. Apart from significant advancements in plant varieties and agrotechnology, satellites and drones, electronic maps and meta-image processing, precise farming, and other technical areas, this decision-making process is still not automated, relies heavily on knowledge and experience, is informal and manual, requires a lot of time and money, and is very risky for business and farm owners. They believe that certain things are more urgent than others and that some are less urgent. Additionally, they schedule the work according to what they deem urgent. They make decisions based on their thoughts and emotions, and operational choices are typically made based on expenses without considering their effects on the value stream. Without understanding the long-term and financial consequences of any preferences, a grower may engage in low-impact activity as they perceive it to be more crucial and put a significant value at risk.

All businesses, including Greenhouses, must consider the opportunity cost when deciding which task to do. Giving management more accurate information makes it easier to identify problems and flaws, minimizes mistakes, streamlines the processes, and enables continuous value stream improvement.

Real-time data collection and analysis combined with modern visualization approaches, made possible by Digital Twin-Value Stream, can contribute to increased process transparency and optimization, affect people's behavior, enable intelligent decision making, and better documentation and communication. Following IDEF0 A-0, figure 11, highlights the key components of a hypothetical Digital Twin-Value Stream for Greenhouse agriculture and what would happen if it were to be implemented.

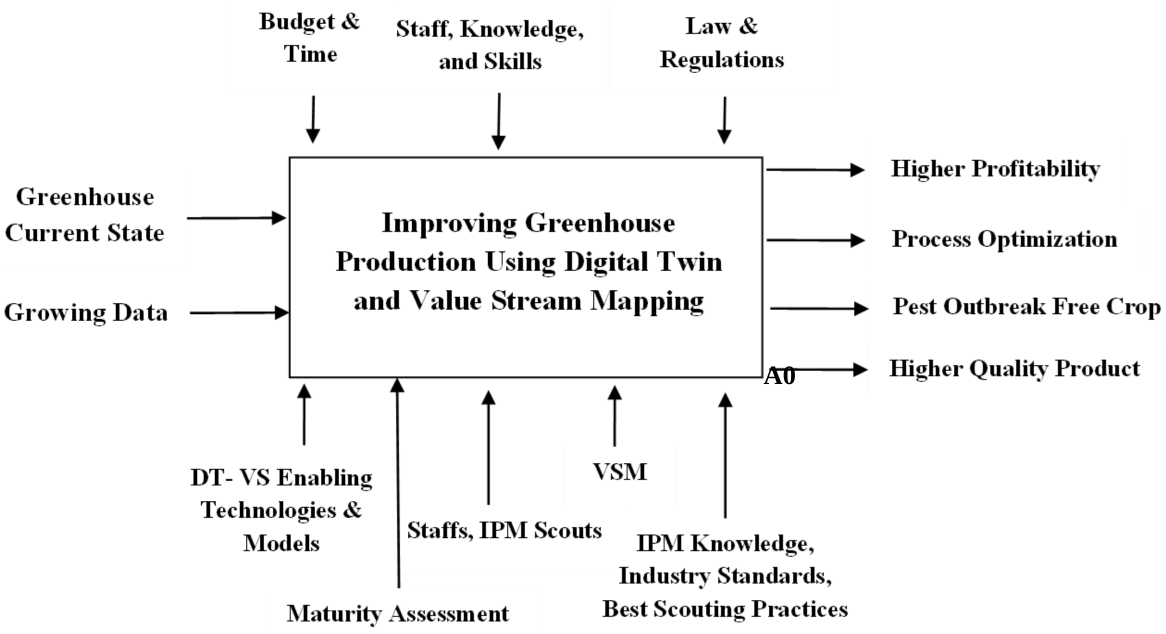

Figure 11: IDEF0 A-0: Key Components of a DT-VS for High-Value Greenhouse Products

The key inputs needed:

1. Business Model of Greenhouses.
2. Key business processes of crop cycle in Greenhouse agriculture and their sequence.
3. Their People responsibilities or accountabilities for those processes, and their skills level.
4. Their Key Success Factors Indicator.
5. Yield standard from either their supplier of seed or their crop consultant.
6. Financial information for the input and output of growing.
7. Existing database [environment control data and yield data, etc.].
8. IPM Scouts report.
9. Existing best and worst practices [their highest and lowest performance in the past].
10. Available technology in the Greenhouse.
11. Growing inputs [seeds, fertilizers, pesticides, bags, growing media, etc.].

The mechanisms or tools needed:

1. IPM Scouts, Skilled labors, and technology transition team.
2. Industry standards for the quantity and quality of throughput of different processes by a crop consultant.
3. The reproductive rate of the insects related to temperature & humidity.
4. Comprehensive IPM Knowledge like Non-beneficial pests, Action thresholds, Pest control and prevention methods, etc.
5. Standard solutions to address process inefficiencies [by crop consultants/ industry leaders and practices].
6. Best scouting practices and scientific approaches to choosing Bios, Quantities, and applications.
7. Maturity assessment model and questionnaire.
8. Value Stream Mapping tool.
9. Environment Control System.
10. Industry 4.0 technologies like Artificial Intelligent apps, Robots and Drones, Sensors, Mobile devices, QR Code Reader, Machin Learning and Data Mining algorithms and Data Analysis.
11. Cost-Benefit analysis techniques for technology adoption.
12. Prioritization Techniques.

The constraints for this model would be:

1. Implementation Budget & Time.
2. Skill level of the Staff.
3. MOE and health Canada regulations.

Moreover, the final output is a Digital Twin-Value Stream System that support:

1. Higher profitability.
2. Process optimization.
3. Pest outbreak free crop.
4. Higher quality products.

2.6. Maturity Assessment Model

Technological advancements have resulted in significant changes in how companies operate in the modern day. Despite a growing willingness to invest in digital transformation, decision-makers need an understanding of their current state and the capability to apply this technology and have a piece of strategic advice toward its implementation. As a result, it is critical to establish and create a set of guidelines for evaluating the current state of the company in its path of transitioning to DT.

Maturity Assessment Models (MM), also called readiness models, are usually used to conceptualize, and measure the level of maturity (process, organization, or objective) to capture the starting point and allow for initializing the development process (Azevedo and Santiago, 2019). Each stage reflects a different level of development, and later stages are preferable to early ones, with the greatest level representing excellence (Asdecker and Felch, 2018). (Rafael *et al.*, 2020) Detailed the main components of a MM in their study.

The distinction between maturity and readiness models is that readiness models are used to assess readiness prior to involvement in the process and to ensure that all essential conditions and preparations for the use of technology have been satisfied. Processes, systems, corporate culture, and other qualities were described and captured using maturity models as part of the maturation process. Roadmaps were mainly used in the planning and development of technologies (Zoubek *et al.*, 2021). The growing number of publications in this field, as shown in figure 12, demonstrates the significance of this method.

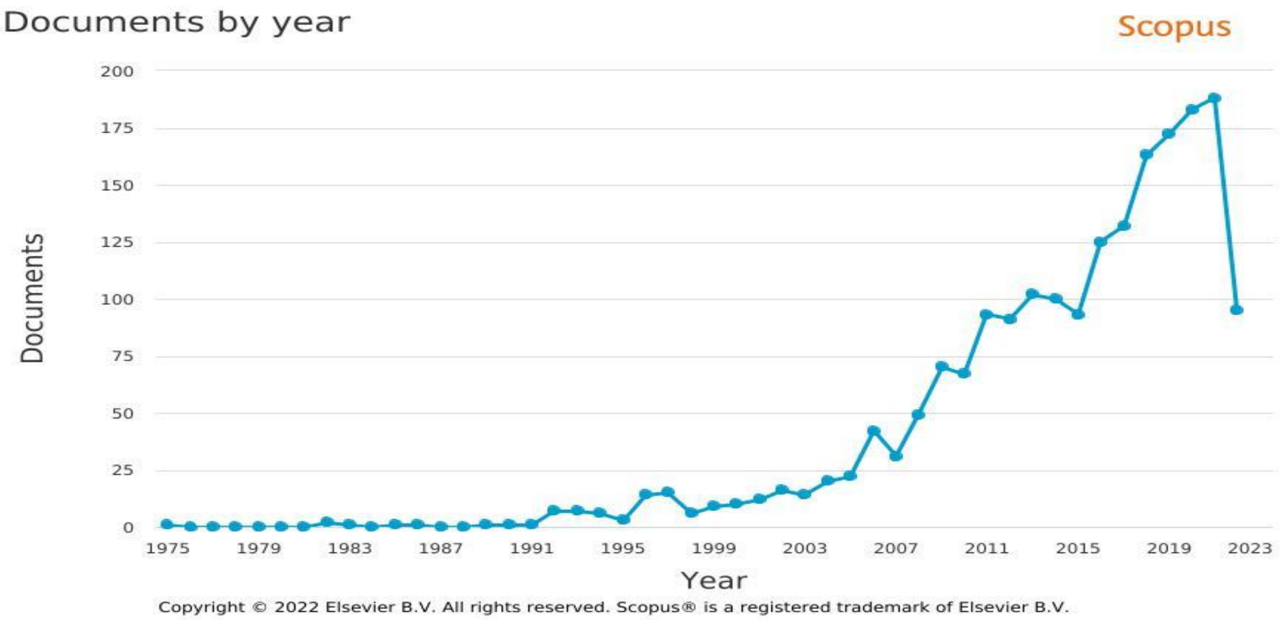

Figure 12: The growth in papers on the "Maturity Assessment Model" as shown in Scopus.

According to (ElMaraghy *et al.*, 2021), maturity models are used as progress indicators to assess the gap between the status of research and actual industrial practice. In their study, they looked at various manufacturing system maturity models. Said by their thorough review, “Most German and the Korean maturity models generally focus on technology, automation and production, and many German models specifically cater to SMEs. The American and international models often focus on connectivity, corporate culture, and finance or the company indicating the current technological mid-term outlook. The Singapore smart industry readiness index (SIRI) assesses Industry 4.0 based on processes, technology, and organization criteria.” A few instances are provided following. As a foundation for production-specific maturity models, the capability maturity model integration (CMMI) and the process and enterprise maturity model (PEMM) are generally applicable. The organizational, IT, performance management, and information connectivity maturity characteristics are all examined by the smart manufacturing system readiness assessment model (SMSRL). The measuring categories are the processes, personnel, software, output data format, key performance indicators (KPI), and KPI relationships. Five components make up the small and medium-sized enterprise smart manufacturing maturity model (SM3E), which was established in the US and Mexico. These categories are finance, people, strategy, process, and product. By evaluating methodological capabilities and organizational culture, PEMM, “Leitfaden Industrie 4.0” and the “Reifegrad fur Industrie 4.0” analyze an organization's maturity level, and they emphasis the flow of information and the use of data in the production process. The Industry 4.0 "Reifegrad Test" evaluates the maturity of sales and customer service, logistics and warehouse management and administration, research and development, and production. The SIMMI 4.0 assesses the degree of development of digital products, cross-sectional technologies, and information flow across the supply chain and all levels of the hierarchy. The Korean assessment framework examines the level of sophistication in intelligent manufacturing with reference to the incorporation of data analytics in both production and finances.

According to (Tonelli *et al.*, 2016), the authors outline a revolutionary methodology for manufacturing value modelling, that goes from the strategic level down to operational improvements. The Manufacturing Value Modeling Methodology (MVMM) is based on 5 steps: value map, maturity model, gap and process analysis, validation, and improvement areas definition. In this study, a series of structured interviews were conducted using this methodology to develop the value map following the present firm maturity model and the connections between the strategic objectives and operational practices, competencies, and methodologies. (Schumacher, Nemeth and Sihn, 2019) Provided a 10-step process that leads businesses step-by-step from the moment they learn about Industry 4.0 till they create its roadmap, action-fields, and realization projects. Based on a literature review conducted for their study, (Azevedo and Santiago, 2019) stated that the so-called Technology-Organization-Environment Framework is one of the most widely used approaches for evaluating how technology affects businesses. According to the theory supporting this framework, the technological context consists of the key external and internal technology for the company, organizational context, which relates to the firm's capabilities and resources; and environmental context, which covers the competition for the firm, the size and structure of the industry, and the regulatory framework, all have an impact on how a firm absorbs and executes technological advancements. Therefore, they evaluated the industry 4.0 maturity model through six dimensions: products and services, manufacturing, strategy, supply chain and interoperability. Later, Industry 4.0 maturity model assessing environmental attributes of manufacturing company presented by (Zoubek *et al.*, 2021). To find key processes with potential for the environment, they used value stream mapping (VSM). (Santos and Martinho, 2020) Proposed an Industry 4.0 maturity model which has 41 components considering five dimensions: organizational strategy, structure, and culture; workforce; smart factories; smart processes; and smart products and services. (Rafael *et al.*, 2020) Adopted IMPULS to develop an Industry 4.0 maturity model tailored for the Machine Tool (MT) industry to give MT manufacturers—particularly small and medium-sized enterprises—a comfortable, user-friendly, and accessible self-assessment tool to help them analyze where their businesses stand in the context of digitization and Industry 4.0. This suggested model evaluates the company in terms of its employees, strategy and organizational structure, smart factory, data-driven, smart operation, and smart products dimensions, as well as the sub-dimensions connected to each of these dimensions. In the context of Industry 4.0, another study by (Wagire *et al.*, 2021) presented a technology-focused, empirically based maturity model to evaluate the level of maturity of Indian manufacturing organizations. The model has 38 maturity components spread across 7 dimensions, including people and culture, industry 4.0 awareness, organizational strategy, value chain and process, smart manufacturing technology, product and services-oriented technology, and industry 4.0 base technology. By developing an adopted model by (Bandara, Tharaka and Wickramarachchi, 2019) with the intention of performance as well as for continuous improvement, the authors evaluated the industry 4.0 maturity of the Sri Lankan banking sector via a selected sample of 10 banks. They stated, "in order to attract leads as well as to retain customers, it is important to understand current performance of industry 4.0 in order to focus on continuous improvement to offer better customer satisfaction." Also, to evaluate how well healthcare institutions are using human-machine collaboration technologies, (Fenton, 2022) established the Smart Maturity Model for Health Care (SMMHC).

According to literature surveys, there are several industry-specific maturity assessment models. However, a maturity assessment model designed explicitly for greenhouse agriculture to assess the greenhouse's current state, including its processes, resources, and capabilities, and identify the gaps between the current state and the desired state, which is a measure of readiness for implementing a DT-VS, may be beneficial for successfully transitioning toward becoming a smart lean greenhouse, and adopting value stream mapping and digital twin technologies for advanced Greenhouse process management.

2.7. Research Gaps

- The lack of accurate and sufficient data is a significant barrier to traditional Greenhouse farming, and growers make daily decisions based on costs rather than actual needs. Most farms and Greenhouse agriculture businesses often base their operational decisions on costs rather than actual needs. They disregard the value that may be jeopardized due to pest infestation brought on by improper farming practices and fail to consider the deadly waste that occurs in agriculture.
- Digital Twin-Value Stream (DT-VS) is an emerging technology that can benefit this industry by providing decision-makers with more precise insight into their operations by employing a Digital Twin at the value stream level.
- However, to utilize such technology in greenhouses, understanding where they stand is a prerequisite for deciding future actions. Tools like the Maturity Assessment Model may be very useful for effectively implementing a DT-VS. They may help identify the business's starting state, capacity, and readiness toward digitalization and produce a development roadmap.
- There are several sector-specific MMs. However, a very limited number of them are constructed for developing a Digital Twin of a Value Stream.
- This study intends to close the gap in the literature about the presence of a Maturity Assessment Model to direct the adoption of the Digital Twin-Value Stream in Greenhouse agriculture.
- Table 1 demonstrates the research gaps based on prior studies.

Table 1: Research Gaps in the existing studies

Author	Source	Business Type			Research Scope					
		Other	Agric.	GH	VSM	DT	DT-VS	MM	DT MM	DT-VS MM
(Nasirahmadi & Hensel, 2022)	Toward the Next Generation of Digitalization in Agriculture Based on Digital Twin Paradigm		*			*				
(Ariesen-Verschuur et al., 2022)	Digital Twins in greenhouse horticulture: A review			*		*				
(Frick & Metternich, 2022)	The Digital Value Stream Twin	*					*			
(Verdouw et al., 2021)	Digital twins in smart farming		*			*				
(Chaux et al., 2021)	A digital twin architecture to optimize productivity within controlled environment agriculture			*		*				
(Skobelev et al., 2021)	Digital twin of rice as a decision-making service for precise farming, based on environmental datasets from the fields		*			*				
(Howard et al., 2021)	Greenhouse industry 4.0 – digital twin technology for commercial greenhouses			*		*				
(Pylianidis et al., 2021)	Introducing digital twins to agriculture		*			*				
(Knibbe et al., 2022)	Digital twins in the green life sciences		*	*		*				
(Fatima et al., 2023)	Digital Twin Greenhouse Technologies for Commercial Farmers			*		*				
(Sultan & Khodabandehloo, 2020)	Improvement of Value Stream Mapping and Internal Logistics through Digitalization: A study in the context of Industry 4.0	*			*		*			
(Howard et al., 2020)	Data Architecture for Digital Twin of Commercial Greenhouse Production			*		*				
(Dora et al., 2015)	Lean manufacturing to lean agriculture: It's about time		*		*					
(Lu et al., 2021)	A digital twin-enabled value stream mapping approach for production process reengineering in SMEs	*					*			
(Ronaghi, 2021)	A blockchain maturity model in agricultural supply chain		*					*		
(Wollermann Umpierrez, 2020)	Maturity Assessment of Digital Twin Implementations in the Commercial Aerospace Industry	*							*	
(Uhlenkamp et al., 2022)	Digital Twins: A Maturity Model for Their Classification and Evaluation	*							*	
Proposed Study	A Maturity Assessment Model for Digital Twin-Value Stream Technology in Greenhouses			*						*

CHAPTER 3- RESEARCH METHODOLOGY

3.1. Overview

Greenhouses have a lot going on at the same time. And has numerous goals, yet every firm has limited resources, such as personnel and money. Additionally, there are certain things they feel to be urgent and others that they believe to be less so. They arrange the labor depending on what they consider to be urgent. A grower may do low-impact activity since it is more urgent and puts a significant value at risk without knowing the long-term and financial consequences of any actions. They base their decisions on what is going on in their heads. However, cost of opportunity is the concept that applies to all businesses, including Greenhouses, when you choose to perform one thing over another. In the following, I will offer examples of some regular Greenhouse duties and the consequences of disregarding each due to a lack of resources and the Greenhouse's limitations.

1) Pruning (removing leaves) is essential in Greenhouses since it might reduce crop production if not performed. On the other side, workers must also complete a task called "Foliar plant spray," which includes spraying fertilizers directly on the leaves of plants rather than putting them in the soil. Depending on their priorities, the farmer believes they can spray next week and assign human resources to prune this week. Still, they need to be made aware of how many pests can multiply in a single week or the financial costs associated with pest multiplication, and the value at risk of delaying one process/ task. For example, 1) if they already have ten pest-infested spots, if they neglect to spray this week, with pest multiplication rate, it will be 50 spots next week. 2) In about six weeks, one thrips female will multiply to 6000. In the instance above, they would remove the sprayed bios from the leaves if they sprayed this week and pruned them the following week. Although they spend more money and time on fertilizer by doing it first, removing the leaves and bios reduces the spray's efficacy. Again, people decide without considering the value at risk.

2) The other scenario: After the de-leafing process, they throw all those thrips-infested leaves on the floor, and when we ask whether they can't take them off, they inform us they don't have enough labor, even though these thrips might cause them more harm than labor expenses. Calculations show that the cost of labor is 11,000 CAD, while the cost of not removing the leaf is more than 100,000 CAD.

So, because there is no digital system to foresee, compute, and learn from this occurrence, a grower is attempting to save 11,000 while unconsciously accepting the risk of 100,000.

The human mind is sequential. It means they can consider just a restricted number of causes and effects. We generally do not see the possible process sequences and value at risk. One choice we make today might significantly impact many things next week. The challenge is that we don't have any way to calculate the value at risk for not following the proper process at the right time.

Based on a review of the literature in the Digital Twin and Value Stream field, it was found that studies on the agriculture sector, mainly Greenhouse agriculture—the focus of this research—are less common than those on other industries like manufacturing.

The term "Digital Twin-Value Stream" was chosen for this study because the digital twin seeks to enable value stream management in Greenhouse agriculture and lay more focus on the significance of the work processes, their order, their effects on the value stream, and how technology adoption can support value stream optimization, which is frequently disregarded in DT development and farmers' decision-making.

By helping Greenhouse growers to develop a strategic roadmap for digitalization and employing new technologies like AI, sensors, robots, etc., to develop a Digital Twin-Value Stream, they can take advantage from real-time crop monitoring, timely pest accordance diagnosis, data-based and knowledge-based decision making, etc.

A Maturity Assessment Model for Digital Twin-Value Stream development would be a tool that could assist in a thorough understanding of that industry, its current state, capacity, and resources. Next, we must determine the expected outcomes and client value, specify the target state, and then create a realization path to go from the current state to the one we want to achieve, which is Digital Twin-Value Stream development. This study decided to fill the gap as Greenhouse farming needed a maturity model of this kind.

3.2. Integrated Definition: IDEF0

Graphical Integration DEFinition language (IDEF) is a useful tool for representing actions and their relationships to the task at hand using graphics (diagrams) and text that identifies inputs, outputs, mechanisms, and constraints/ controls (ElMaraghy, 2021).

The main objective of this study is to design a Maturity Assessment Model with the aid of a systematic design approach to support the development of the Digital Twin-Value Stream in the Greenhouse agriculture sector. IDEF0 A-0, figure 13, represents the context-level view of the topic under study, and IDEF0 A0, figure 14, represents the decomposition of the context diagram, respectively.

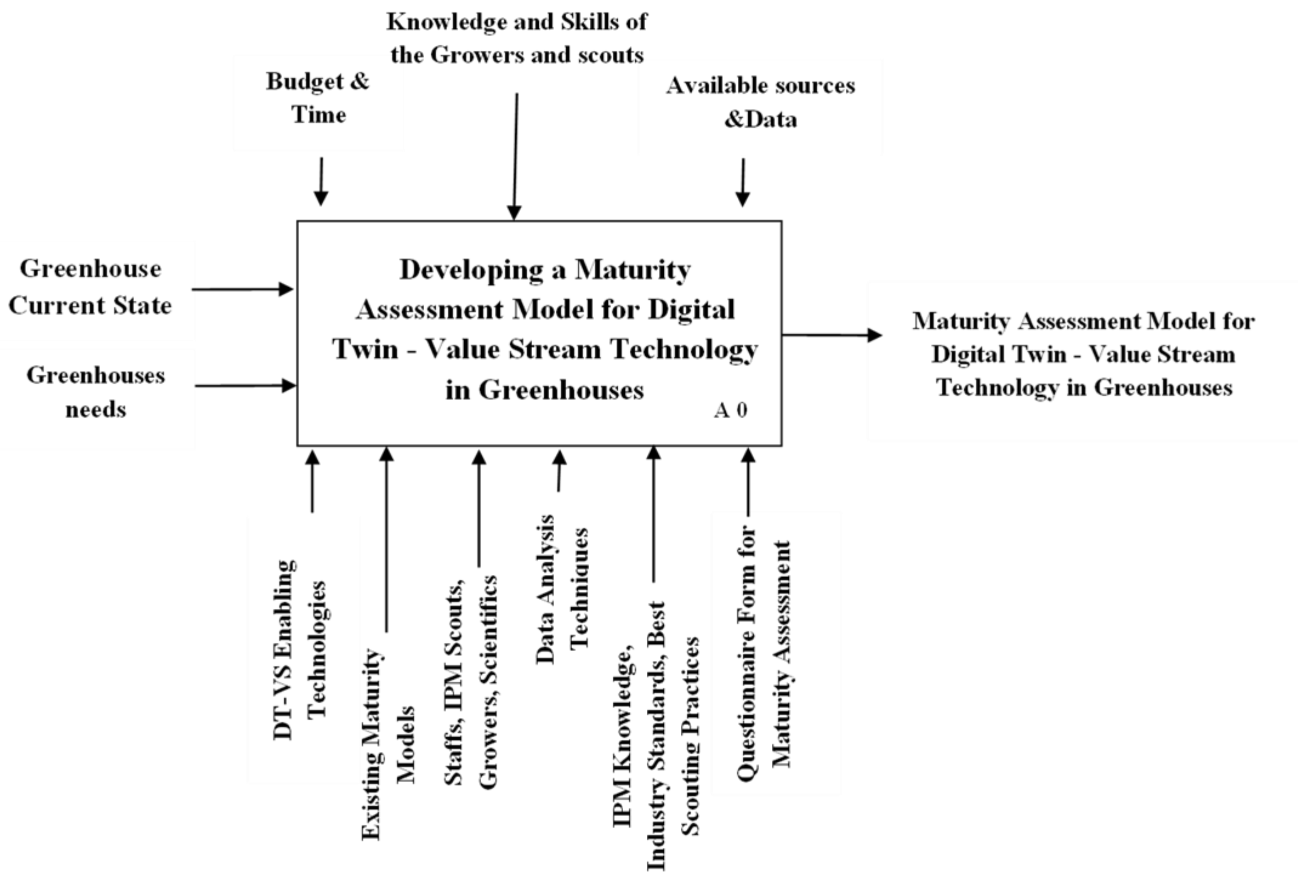

Figure 13: IDEF0 A-0- Developing a Maturity Assessment Model for DT-VS Technology in Greenhouses

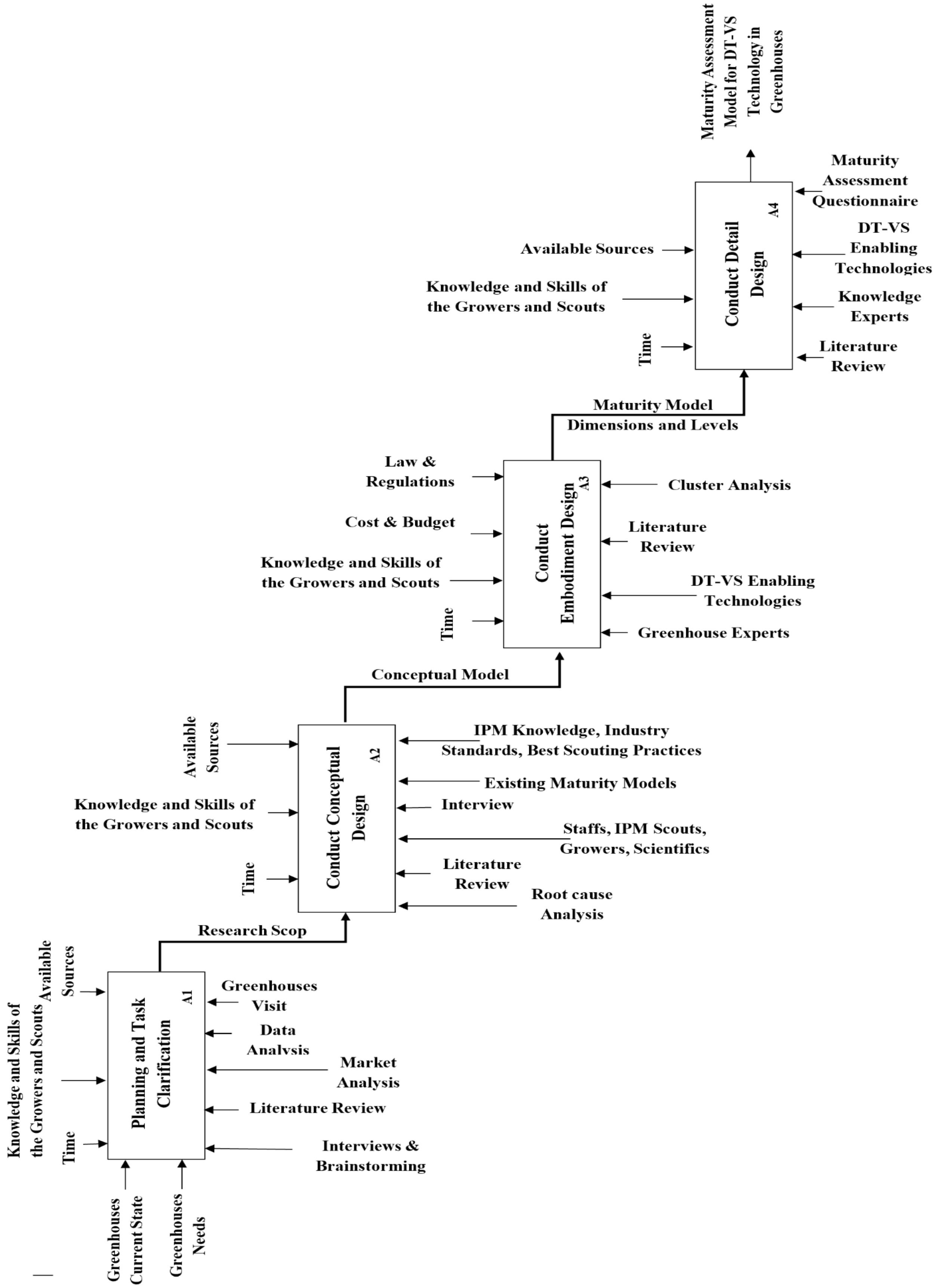

Figure 14: IDEF0 A0- Developing a Maturity Assessment Model for DT-VS Technology in Greenhouses

3.3. Systematic Design Approach

This study was created using a systematic approach by Pahl & Beitz(Pahl *et al.*, 2007). This strategy was chosen because it offers an effective mechanism for simplifying the processes and facilitates achieving the goal using a step-by-step procedure.

To develop the Maturity Assessment Model using systematic design, there are 4 phases.

3.3.1. Planning and Task Clarification

Every business that has decided to start an enterprise-wide digital transformation journey must evaluate its level of readiness to determine whether the business is prepared for a significant change and the transformation process. Through this assessment, decision-makers can learn more about their current capabilities and assets and receive the confidence that they will only start a transformation project that they are prepared to finish. To design and develop a relevant maturity assessment model for a particular industry, we need a thorough understanding of that specific sector and the factors affecting it. The task clarification in this research is to gather data on the needs that the developed maturity assessment model must consider to give appropriate guidance for building a Digital Twin-Value Stream in the Greenhouses, as well as about the current limits and their significance. Therefore, access to up-to-date information is crucial, and this study used various techniques to obtain it:

3.3.1.1. Data Collection

1. **Interview:** Interviews were conducted with several experts in the field, such as Greenhouse growers, IPM scouts, and Biopesticide Scientifics, who were willing to respond to a variety of questions to investigate the current state of the business, industry strategy and terminology, their maturity in using technology, hidden obstacles, workforce capabilities, and stakeholder expectations.

2. **Observation:** The understanding of the current procedures, infrastructure, and culture, as well as the discovery of prospective improvement ideas, were all enabled by visiting a few Greenhouses.

4. **Literature review:** Review the literature in the subject area that has been investigated, disputed, and established. A systematic literature review was applied to find existing maturity models in the context of Digital Twin and VSM- a Lean Manufacturing tool in the databases of Scopus, and Google Scholar. Only the results considered relevant

for the aim of this study, which focused solely on approaches to measure company maturity under process improvement and technology adoption aspects, were collected. Around 200 articles were identified with the search terms. As part of the second filter, before reading the articles in full, the studies' conformity was assessed by looking at their keywords, titles, and abstracts. Thirty-nine papers are therefore deemed qualified for further evaluation. The publications that were closest to the study's purpose, 15 articles, were chosen for detailed review and an in-depth analysis of each of the models to filter out those that met the needed requirements.

5. **Market research:** Data on target markets, environmental factors, Greenhouse characteristics, and advantages and disadvantages of outdoor farming vs. Indoor farming have all been collected in a systematic manner.

3.3.1.2. Data Analysis and Classification

After reviewing all the data collected using various methods, the most typical issues for Greenhouses were identified and grouped as follows:

Table 2: The most frequent issues in Greenhouses

#	Key Issues
1	Yield loss due to employee limitation, ad hoc decision-making, and lack of supply chain integration.
2	Yield loss due to pest outbreak.
3	Yield loss due to plant toxicity.
4	Yield loss due to factors like temperature, moisture, humidity, fertilization, light, irrigation, seeds, pesticides, etc.)
5	Yield loss due to lack of IPM knowledge, proper training, standard operation procedures (SOPs), and employee performance.
6	Monetary losses because of highly variable and fixed Greenhouse management costs, as well as low profitability due to yield loss.

Based on brainstorming sessions with SMEs in this field, most issues farmers confront are yield loss due to employee limitation, ad hoc decision-making, lack of supply chain integration, and yield loss caused by pest outbreaks, respectively. Further investigations showed that the other issues stated can be one of the causes or a consequence of this primary issue. As a result, the other issues can also be resolved if we can prevent/ manage pest outbreaks, and improve decision-making processes, the Pareto principle (also known as the 80/20 rule).

3.3.2. Conceptual Design:

Following the task clarification and problem description phases, the conceptual design phase establishes the primary solution by separating the key issues, seeking feasible potential solutions, and combining them into a starting point. To identify the underlying reasons for a pest infestation in a Greenhouse, the key issue determined in the previous stage, and possible remedies and technologies, a root cause analysis is undertaken at this step.

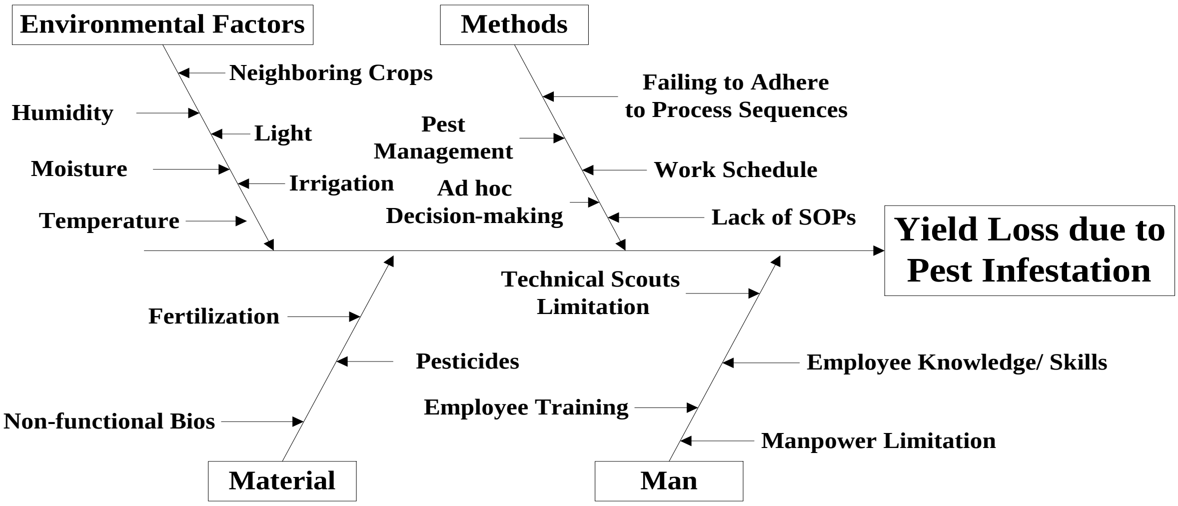

Figure 15: The Underlying Causes for Pest Infestation

Based on a survey of the literature and SMEs' input, the IPM program would be the most practical solution when considering the underlying reasons for pest infestation in a crop. However, as was already noted, there are difficulties in conventionally implementing this program. To strengthen this program, we must consider cutting-edge technology adoption. As was previously discussed about the advantages of DT, for a specific entity such as Greenhouses, we might have different forms of DT. One potential DT for the current issue would be developing a DT-VS to quantify the value at risk and value leakage due to pest infestation due to not following the proper processes at the right time and help the growers in proactive planning and resource management to optimize advantages. To develop such a system, we must first check their current situation and then decide where they should reach. Therefore, A maturity assessment model is required to assess the readiness of a Greenhouse for the DT-VS deployment and technology adoption and specify the requirements that must be satisfied. When designing the maturity assessment model for developing DT-VS, Greenhouse agriculture processes and IPM knowledge should be one of the key mechanisms. Processes and how they are carried out are crucial to the IPM program since failure to apply the proper procedure or sequence could result in a pest infestation. As a result, value stream mapping and IPM knowledge can complement one another. And by giving them access to real-time data and in-depth analyses of what-if scenarios in crop production, protection, and its value stream processes, the DT and its enabling technologies may empower both VSM and IPM.

3.3.3. Embodiment Design:

The design of the maturity assessment model structure and its key pillars, such as the maturity levels, Building Blocks. And dimensions, as well as the justification for the selection of these components, are all important considerations that must be made throughout the construction of a maturity assessment model. Each maturity level, dimension, and Building Block must also be described in terms of its features. This phase involves determining approximate maturity Building Blocks and maturity levels for the functional structure of the maturity assessment model based on conceptual design.

3.3.3.1. Maturity Assessment Building Blocks

In any firm, it's important to recognize potential risks, consider their significance and possibility, develop response strategies, successfully implement them, and keep a constant watch out for emerging threats. One of the major concerns associated with Greenhouses is pest infestation. When this occurs, farmers must spend a lot of money on pest control strategies and may not be able to entirely get rid of the pests, which could cause them to lose all or a significant portion of their crops or product that is of lower quality. Numerous internal factors in the Greenhouse contribute to the spread of pests and unforeseeable external ones. Examples include the way Greenhouse activities are carried out, the Greenhouse's environmental conditions, the knowledge and abilities of the staff, the farmers' risk management techniques, and the crop's chosen methods of growth and protection. Several pest risk management strategies can be employed, depending on the resources, technology, level of expertise, and expected revenue of the Greenhouse's output.

In this stage, we're interested in learning which aspects of Greenhouse farming can negatively impact the processes or be impacted by them to develop an optimization approach. An extensive examination of all existing maturity models in other sectors that could be relevant to the work being assessed, a comprehensive list of all potential maturity levels, building blocks, and dimensions on existing studies compiled; Technology, People, Strategy, Processes, and Products were the five most prevalent Building Blocks identified after clustering information from existing models.

To extract requirements that are considered necessary to be analyzed through the maturity assessment model to support the development of a Digital Twin-Value Stream for the Greenhouse sector, brainstorming sessions with subject matter experts were arranged to decide what further dimensions might be added to the current list.
Figure 16 and Table 3 respectively demonstrate the maturity building blocks along with the description for each, inspired by (Azevedo and Santiago, 2019; Bandara, Tharaka and Wickramarachchi, 2019; Schumacher, Nemeth and Sihn, 2019; Rafael *et al.*, 2020; Santos and Martinho, 2020; Caiado *et al.*, 2021; Wagire *et al.*, 2021).

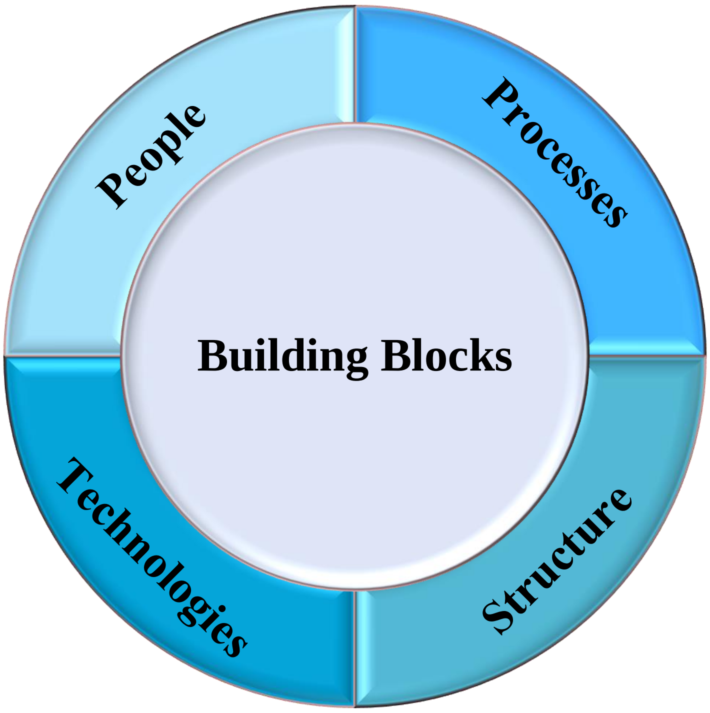

Figure 16: Greenhouses' Technology Adoption Building Blocks for Digital Twin-Value Stream Maturity Assessment Model Development

Table 3: The Contribution of Maturity Assessment Building Blocks to the Success of Greenhouse Agriculture

#	Building Block	Definition
1	Business Structure	This building block focuses on short- and long-term strategies and decisions for managing Greenhouse operations, which will impact how the processes are carried out. If decisions are made based on price rather than how they will affect the value chain, if one action is preferred over another without taking opportunity costs into account, if a reactive pest risk strategy is chosen rather than a proactive one, and so on, this will not only hurt Greenhouse profit but also the ecosystem's life cycle.
2	Processes	This building block focuses on the primary agricultural cycle processes (crop planning, planting, growing, and harvesting) and crop protection processes (pest preventing activities, pesticide methods and timing, etc.). The likelihood of yield loss would be substantial if the sequence of processes were not rationally established, a clear and understood SOP was not provided and applied, and appropriate pest protection efforts were not planned.
3	People	This building block focuses on the workforces' knowledge and performance. A significant amount of yield loss may result from improper SOP adherence, lack of training, or high turnover rates.
4	Technologies	This building block focuses on the application of advanced technologies in streamlining Greenhouse agricultural operations. It is vital to adopt technologies that considerably improve various Greenhouse agricultural operations while remaining economically viable due to the limited resources available.

3.3.3.2. *Maturity Assessment Levels*

As previously said, several cutting-edge and intelligent technologies, along with their prerequisites, must be employed in order to minimize risks, optimize processes, and maximize benefits.

Therefore, based on different approaches to confront and respond to new ideas for improvement or future changes, methods to manage processes, and the level of capability and knowledge of staff and stakeholders, we can define different levels of maturity for Greenhouses in process management and technology adoption to improve it.

Therefore, it is essential to define and measure the maturity level of various building blocks and dimensions in order to be aware of it, better grasp the situation at hand, and make plans based on the gaps found.

Figure 17 and Table 4, respectively, demonstrate the different "Maturity Levels" of the proposed "Maturity Assessment Model" and maturity levels for each building block, and each of them is described in detail below. The Greenhouse can be at any maturity level between 1 and 5, with 5 being the maximum. A higher level denotes enhanced procedures and processes, more knowledgeable people, more informed decision-making, and a greater maturity in the technology transition.

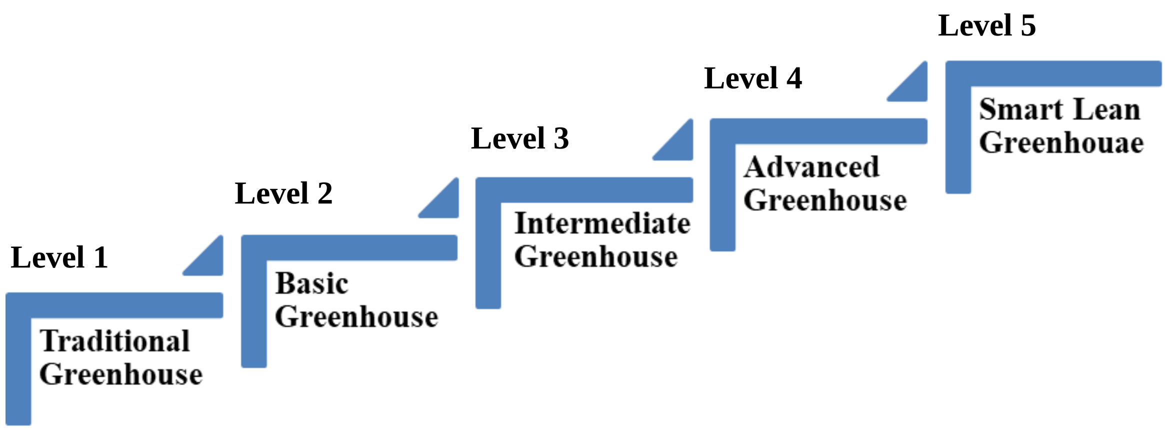

Figure 17: Greenhouses' Technology Adoption Maturity Levels for Digital Twin-Value Stream Maturity Assessment Model Development

Table 4: Maturity Levels of Each Building Block in the Proposed Maturity Model Assessment

#	Maturity Levels / Building Block	Level 1	Level 2	Level 3	Level 4	Level 5
1	Business Structure	Not Exist	Basic	Intermediate	Advanced	Aligned Greenhouse
2	Processes	Traditional Greenhouse	Basic	Intermediate	Advanced	Lean Greenhouse
3	People	Unaware	Basic	Intermediate	Advanced	Expert
4	Technologies	Traditional Greenhouse	Basic	Intermediate	Advanced	Smart Greenhouse

1) **Traditional Greenhouse:** Greenhouse production processes (e.g., crop planning, planting, growing, harvesting, packaging, and sorting), crop protection processes (e.g., pest-preventing activities, pesticide types, their application method, timing, etc.), and value chain processes (e.g., material ordering volume, procurement lead time, logistics conditions, etc.) are not defined and planned, they are carried out based on experience, and they are not monitored and efficient enough. The processes are not automated, humans execute all Greenhouse processes, and there is no link between different processes. There is no plan for improving Greenhouse processes and utilizing technology to support and facilitate process improvement, or limited plans are defined and implemented. Greenhouse's daily and managerial decisions are ad-hoc and made without supporting analysis. There is no risk mitigation or contingency plans (For instance, people risk like shortage of human capital, lack of training and resource management, process risk like not adhering to the proper procedures, and product risk like the occurrence of pest infestation). Greenhouse staff and stakeholders lack the necessary knowledge and skills to carry out Greenhouse agriculture processes effectively and use existing technologies properly, and refrain from embracing new ideas, technology, or potential changes and actively avoid them.
2) **Basic:** Greenhouse production processes, crop protection processes, and value chain processes are defined but not well documented. They are planned and observed occasionally and carried out based on experience. Humans execute Greenhouse processes with the assistance of basic automation, and some processes are formally linked. Short- and long-term plans for improving Greenhouse processes and utilizing technology to support and facilitate process improvement are defined and clearly conveyed to staff members and other stakeholders. Greenhouse's daily and managerial decisions are experienced- or price-based. Growers are willing to take risk. Their strategy for addressing Greenhouse risks is a reactive approach, and when a pest problem arises, they implement corrective action. Greenhouse staff and stakeholders are informed about the importance of conducting Greenhouse agriculture processes efficiently and employing adopted technologies. They neither agree nor disagree with new ideas, technology, or potential changes.
3) **Intermediate:** Suppliers, inputs, processes, outputs, and costumers are clearly defined. Greenhouse production processes and crop protection processes are defined and documented but not standardized. Processes are regularly planned based on how urgently we currently need to do them and resource availability. The lack of resources

may force the withdrawal or change the order of some processes. Value chain processes are managed based on top priority factors (e.g., suppliers' lead time, quality, price, etc.). Some processes are carried out based on SOPs, and sometimes are checked by physical observation or smart devices like QR code readers to evaluate their efficiency and adherence to SOPs. Some lean manufacturing principles and tools are employed to reduce/ eliminate process wastes (e.g., motion, over-processing, handling) and improve them. The processes are partially automated with significant human intervention, and all internal processes are formally linked. Short- and long-term plans for improving Greenhouse processes and utilizing technology to support and facilitate process improvement are defined and clearly conveyed to staff members and other stakeholders, the timeline is set, and proper funding and resources are allocated. Greenhouse's daily and managerial decisions are based on awareness and knowledge obtained from research and reviewing scientific information. Growers strive to lessen the degree and likelihood of pest harm by engaging in several activities, like Integrated Pest Management (IPM), and their strategy for addressing Greenhouse risks is preventive approach. Some Greenhouse staff and stakeholders are trained at conducting Greenhouse agriculture processes efficiently and employing adopted technologies. They accept changes in principle, like technology adoption or process optimization, but they have not yet committed.

4) **Advanced:** Standard Operational Procedures (SOPs) exist for some Greenhouse production and crop protection processes, and the Value Stream is mapped. Processes are planned based on their logical sequence, scientific significance, and multiple factors (e.g., seeds type, residual chemicals, beneficial bios, cost of opportunity, etc.). Then required resources are planned and assigned. Some processes are carried out based on SOPs, and routinely are checked by physical observation, smart devices like QR code readers, sensors, or cameras to evaluate their efficiency and adherence to SOPs. Some lean manufacturing principles and tools are employed to reduce/ eliminate process wastes and improve them. The processes are almost automated with minimal human intervention, and some value chain processes are formally linked. Several plans for improving Greenhouse processes and utilizing technology to support and facilitate process improvement are carried out. Greenhouse's daily and managerial decisions rely on Greenhouse's historical data and data analysis. Growers predict and eliminate cause of pest infestation using historical data, data-driven analysis, algorithmic trends, experts' experience and knowledge in this field, and

their strategy for addressing Greenhouse risks is predictive approach. Greenhouse staff and stakeholders are all trained at conducting Greenhouse agriculture processes efficiently and employing adopted technologies. They understand the value of changes and try to incorporate them into their daily activities.

5) **Smart Lean Greenhouse**: There are Standard Operational Procedures (SOPs) for almost all Greenhouse production and crop protection processes. The Future Value Stream is mapped. Processes are planned and adjusted based on the dynamic condition of the Greenhouse (e.g., resource depletion, pest issues, material delivery, etc.). All processes are carried out based on SOPs, and are checked in real-time by physical observation, smart devices, sensors, cameras, robots, or drones, etc. to evaluate their efficiency and adherence to SOPs. Many of lean manufacturing principles and tools are applied to almost all processes to reduce/ eliminate process wastes and improve them. The processes are almost automated with minimal human intervention, and digital simulation is used to improve performance and efficiency and test what-if scenarios. All internal and value chain processes are formally linked and integrated. Several plans for improving Greenhouse processes and utilizing technology to support and facilitate process improvement are carried out, and the success or failure of the plans is regularly assessed, and plans are modified as required. Greenhouse's daily and managerial decisions rely on a decision support system (DSS). Growers using advanced risk management approach for addressing Greenhouse risks. They employ sensors and advanced technologies such as Industry 4.0 for real-time condition monitoring and determining the signal for risk before it happens. Also, the system or smart devices will inform growers of any risk probability and provide them with possible solutions. Greenhouse staff and stakeholders are experts at conducting Greenhouse agriculture processes efficiently and employing adopted technologies. They embrace changes and actively plan and experiment with new methods and emerging technologies.

3.3.4. Detailed Design:

During the detailed design phase, a comprehensive maturity model was developed. It consists of maturity levels, building blocks, and dimensions, with thorough explanations, a systematic questionnaire form for each dimension, a detailed maturity assessment procedure, and a method for computing the maturity score.

After all, it would be ready to be used in actual cases to extract the unique requirements and realization plans of each Greenhouse in order to develop a Digital Twin-Value Stream that can improve and optimize the Greenhouse agriculture processes.

3.3.4.1. Maturity Assessment Model

The Digital Twin-Value Stream Maturity Assessment Model for technology adoption in Greenhouses to improve their processes that has been established, consists of four building blocks, ten dimensions and five maturity levels, each of which is evaluated further by its corresponding explanatory component. Table 5 provides an overview of the customized maturity assessment model for the Greenhouse agriculture sector. Based on the assumption that each building block of the model is equally important, its maturity is assessed.

Table 5: DT-VS Maturity Assessment Model for Technology Adoption in Greenhouses

#	Building Block	Dimension	Definition
1	Business Structure Assessment	Vision	Growers and the owner of Greenhouses are clear on how implementing digital technology would promote growth and maintain their competitive advantage.
		Culture	To overcome obsolescence, all Greenhouse stakeholders accept change with no or little resistance.
		Risk Management Approach	Greenhouse growers' managerial style and method of dealing with risks.
		Decision-Making Approach	The accuracy and reliability of decisions they make for their daily operation and Greenhouse management.

#	Building Block	Dimension	Definition
2	Processes Assessment	Production Processes	The degree of production process transparency and documentation, their relationship to one another, and how properly they are carried out.
		Crop Protection Processes	The degree of protection process transparency and documentation, their relationship to one another, and how properly they are carried out.
		Value Chain Processes	The degree of supply chain process transparency, documentation, integrity, and implementation.
		Processes Integration	The degree of integration between production, crop protection, and supply chain processes.
3	People Assessment	Skills & Competence	The right skills and competence for technology adoption are available in the Greenhouse.
4	Technologies Assessment	Technology Capability	The extent to which technology is employed to carry out and manage Greenhouse processes

3.3.4.2. Building Block and Dimension Weighting Factors (WF)

In this Study, each building block and their included dimensions are assumed to be equally important during the maturity assessment model development process for this study. However, in the future, various weights based on various criteria could be applied to each of them. Following table provides the weighting factors (WF) calculation of each dimension.

Total building blocks= 4

Total number of dimensions= 10

Total building blocks weight= 1

building block Weighting Factor (WF)= $\frac{\text{Total building blocks weight=1}}{\text{Total building blocks}}$

Total dimensions weight in each building block=1

building block's dimensions weighting factor = $\frac{\text{Total dimensions weight in each building block}=1}{\text{Total dimensions in each building block}}$

Total dimensions weight= $\sum Building\ block\ weight\ i * \ Dimension\ weight\ j$ =1

Where i=1,2,3,4 and j= 1,…,10

Table 6: Maturity Building Block and Dimension's Weighting Factor

# BB	Building Block (BBi)	BB Weight	Dimension (Dj)	BB Total Dimensions	BB Dimension Weighting Factor
1	Business Structure	0.25	Vision	4	0.25
			Culture		0.25
			Risk Management Approach		0.25
			Decision-Making Approach		0.25
2	Processes	0.25	Production Processes	4	0.25
			Crop Protection Processes		0.25
			Value Chain Processes		0.25
			Process Integration		0.25
3	People	0.25	Skills & Competence	1	1
4	Technologies	0.25	Technology Capability	1	1

3.3.4.3. DT-VS Maturity Assessment Model Questionnaire for Greenhouses

The idea of what questions should be included in this research questionnaire was formed after evaluating all current maturity assessment questionnaires that can be connected to this research topic. The initial questionnaire was then prepared. Peers then reviewed the questionnaire, and after considering their suggestions and criticism, the ideal questionnaire for this research was created. The following tables, 7-18, include the questionnaire, the scores assigned, and the pertinent rationale. The scores were taken out of the questions and made available to the interviewees as a selective option to prevent prejudicial responses. Additionally, there are three sections to this questionnaire: the opening questions, which focused on general background information on the Greenhouse under consideration; the main questions concerned assessing the level of technological adoption maturity in that Greenhouse and readiness for DT-VS development and will be incorporated to further analyses, and the closing questions that will be employed to accept or decline the research's hypothesis.

Table 7: General Information Questions

General Information		
Greenhouse Background		
#	**Description**	**Response**
Q 1)	**Greenhouse name:**	
Q 2)	**What is the approximate size of your Greenhouse?**	◯ **Large** (More than 50 Acres) ◯ **Medium** (About 25 acres) ◯ **Small** (Less than 10 acres)
Q 3)	**What are your Greenhouse products?** Select all that apply.	☐ **Strawberries** ☐ **Cannabis** ☐ **Tomato** ☐ **Cucumber** ☐ **Pepper** ☐ **Others:** ………….

Table 8: Scores and description of the vision dimension

A. Business Structure Assessment		
Dimension 1: Vision		
Q 1) How do you gauge your success in achieving your set goals for "improving your Greenhouse processes and utilizing technology to support and facilitate process improvement"?		
Options	**Definition**	**Score**
◯	**There is no plan, or limited plans are defined and implemented.**	1
◯	**Short- and long-term plans are defined and clearly conveyed to staff members and other stakeholders.**	2
◯	**The timeline is set, and proper funding and resources are allocated.**	3
◯	**Several plans are carried out.**	4
◯	**The success or failure of the plans is regularly assessed, and plans are modified as required.**	5

Table 9: Scores and description of the cultural dimension

A. Business Structure Assessment		
Dimension 2: Culture		
Q 2) How adaptable do you believe the culture of your Greenhouse staff and stakeholders is to new ideas or future changes for improvement?		
Options	**Definition**	**Score**
◯	**Refrain from embracing new ideas, technology, or potential changes and actively avoid them.**	1
◯	**Neither agree nor disagree with changes.**	2
◯	**Accept changes in principle, like technology adoption or process optimization, but they have not yet committed.**	3
◯	**Understand the value of changes and try to incorporate them into their daily activities.**	4
◯	**Embrace changes and actively plan and experiment with new methods and emerging technologies.**	5

Table 10: Scores and description of the risk approach dimension

A. Business Structure Assessment		
Dimension 3: Risk Management Approach		
Q 3) What strategy do you employ for addressing your Greenhouse risks? (For instance, **people risk** like shortage of human capital, lack of training and resource management, **process risk** like not adhering to the proper procedures, and **product risk** like the occurrence of pest infestation)		
Options	**Definition**	**Score**
◯	There is no **risk mitigation or contingency plans.**	1
◯	**Reactive Approach** (When a problem occurs, they implement corrective action.)	2
◯	**Preventive Approach** (By following proper instructions)	3
◯	**Predictive Approach** (Based on historical data analysis and experts' experience)	4
◯	**Advanced Risk Management Approach** (real-time condition monitoring and determining the signal for risk before it happens. The system or smart devices will inform growers of any risk probability and provide them with possible solutions).	5

Table 11: Scores and description of the decision-making approach dimension

<table>
<tr><th colspan="3">A. Business Structure Assessment</th></tr>
<tr><th colspan="3">Dimension 4: Decision-Making Approach</th></tr>
<tr><th colspan="3">Q 4) What serves as the foundation for managerial and day-to-day decisions in your Greenhouse?</th></tr>
<tr><th>Options</th><th>Definition</th><th>Score</th></tr>
<tr><td>○</td><td>Some or all decisions are ad-hoc and made without supporting analysis.</td><td>1</td></tr>
<tr><td>○</td><td>Some or all decisions are experienced- or price-based.</td><td>2</td></tr>
<tr><td>○</td><td>Some or all decisions are based on awareness and knowledge obtained from research and reviewing scientific information.</td><td>3</td></tr>
<tr><td>○</td><td>Some or all decisions rely on your Greenhouse’s historical data and data analysis.</td><td>4</td></tr>
<tr><td>○</td><td>Some or all decisions rely on a decision support system (DSS).
(a computer program application used to improve a company’s decision-making capabilities by leveraging a combination of raw data, documents, personal knowledge, and/or business models and providing the company with the best possible options)</td><td>5</td></tr>
</table>

<table>
<tr><td>Q 5) What data are you currently collecting for your Greenhouse's managerial and day-to-day decisions?</td><td>1. ……..
2. ……..
3. …….
4. …….</td></tr>
<tr><td>Q 6) How are you analyzing those data?
(Select all that apply)</td><td>☐ Not at all or Traditionally (e.g., manual calculation)
☐ Simple tools (e.g., Excel, Minitab, etc.)
☐ Advanced analysis system and tools (e.g., pattern analysis, dashboards, Machine</td></tr>
</table>

Table 12: Scores and description of the Production Processes dimension

B. Process Assessment			
Dimension 5: Production Processes (e.g., crop planning, planting, growing, harvesting, packaging, and sorting)			
#	**Questions**	**Options**	**Scores**
Q 7)	**To what extent are your Greenhouse <u>production processes</u> <u>defined?</u>**	○ **They are not defined.**	1
		○ **They are not well documented.**	2
		○ **They are documented but not standardized**	3
		○ **There are Standard Operational Procedures (SOPs) for some processes.**	4
		○ **There are Standard Operational Procedures (SOPs) for all processes.**	5
Q 8)	**To what extent are your Greenhouse <u>production processes</u> <u>planned?</u>**	○ **There is no process planning.**	1
		○ **Processes are planned occasionally.**	2
		○ **Processes are regularly planned based on how urgently we currently need to do them and resource availability. The lack of resources may force the withdrawal or change the order of some processes.**	3
		○ **Processes are planned based on their logical sequence and scientific significance. Then required resources are planned and assigned.**	4
		○ **Processes are planned and adjusted based on the dynamic condition of the Greenhouse** (e.g., resource depletion, pest issues, material delivery, etc.)	5

B. Process Assessment			
Dimension 5: Production Processes (e.g., crop planning, planting, growing, harvesting, packaging, and sorting)			
#	**Questions**	**Options**	**Scores**
Q 9)	**To what extent are your Greenhouse production processes carried out?**	○ They are carried out based on experience.	1
		○ **Some processes** are carried out based on their SOPs.	3
		○ **All processes** are carried out based on their SOPs.	5
Q 10)	**To what extent are your Greenhouse production processes monitored and evaluated for their adherence to SOPs?**	○ **Not at all**	1
		○ **Occasionally**	2
		○ **Sometimes**	3
		○ **Routinely**	4
		○ **In Real-time**	5
Q 11)	**How do you collect your Greenhouse processes data?** Select all that apply.	☐ **Not at all**	1
		☐ **Observation and Manual entry**	2
		☐ **People using smart devices** (e.g., QR code reader, mobile scanning)	3
		☐ **Sensors, Cameras**	4
		☐ **Robots, Drones**	5
Q 12)	**Are you using lean manufacturing principles and tools to reduce/ eliminate your Greenhouse process wastes or improve your processes?** (Process waste, e.g., motion, over-processing, handling)	○ **Not at all**	1
		○ **In some processes**	2
		○ **In all processes**	3

Table 13: Scores and description of the Protection Processes dimension

B. Process Assessment			
Dimension 6: Crop Protection Processes (e.g., pest-preventing activities, pesticide types, their application method, timing, etc.)			
#	**Questions**	**Options**	**Scores**
Q 13)	**To what extent are your Greenhouse Crop Protection Processes defined?**	○ **They are not clearly defined.**	1
		○ **They are documented but not standardized.**	3
		○ **There are Standard Operational Procedures (SOPs) for them.**	5
Q 14)	**To what extent are your Greenhouse Crop Protection Processes carried out?**	○ **Not at all.**	1
		○ **They are carried out Occasionally and based on experience.**	2
		○ **They are regularly planned and carried out based on how urgently we currently need to do them and resource availability. The lack of resources may force the withdrawal or change the order of some processes.**	3
		○ **They are planned and carried out based on their logical sequence and scientific significance. Then required resources are planned and assigned.**	4
		○ **They are planned, carried out, and adjusted based on the dynamic condition of the Greenhouse** (e.g., resource depletion, pest issues, material delivery, etc.)	5
Q 15)	**To what extent are your Greenhouse Crop Protection Processes monitored and evaluated for their adherence to SOPs?**	○ **Not at all**	1
		○ **Occasionally**	2
		○ **Sometimes**	3
		○ **Routinely**	4
		○ **In Real-time**	5

Table 14: Scores and description of the Value Chain Processes dimension

B. Process Assessment			
Dimension 7: Value Chain Processes (e.g., material ordering volume, procurement lead time, logistics conditions, etc.)			
#	**Questions**	**Options**	**Scores**
Q 16)	**To what extent are your Greenhouse Value Chain Processes defined?**	○ **They are not clearly defined.**	1
		○ **They are partially defined, but not well documented.**	2
		○ **Suppliers, Inputs, Processes, Outputs, Costumer are clearly defined.**	3
		○ **The current Value Stream is mapped (VSM)**	4
		○ **Future Value stream is developed based on potential process improvement opportunities.**	5
Q 17)	**To what extent are your Greenhouse Value Chain Processes managed?**	○ **There is no plan, and they are carried out Occasionally based on the Greenhouse need.**	1
		○ **Some are usually planned and carried out based on suppliers' availability and price.**	2
		○ **Some are planned and carried out based on top priority factors** (e.g., suppliers' lead time, quality, price, etc.)	3
		○ **They are all planned and carried out based on multiple factors** (e.g., seeds type, residual chemicals, beneficial bios, cost of opportunity, etc.)	4
		○ **They are planned, carried out, and adjusted based on the dynamic condition of the Greenhouse** (e.g., resource depletion, pest issues, inventory level, etc.)	5

Table 15: Scores and description of the Value Chain Processes dimension

B. Process Assessment			
Dimension 8: Processes Integration			
#	**Questions**	**Options**	**Scores**
Q 18)	**To what extent are your Greenhouse Processes Integrated?**	◯ **There is no link between different processes**	1
		◯ **Some processes are formally linked.**	2
		◯ **All internal processes are formally linked.**	3
		◯ **Some value chain processes are formally linked.**	4
		◯ **All value chain processes are formally linked and integrated.**	5

Table 16: Scores and description of the Skills & Competence dimension

C. Skill and Knowledge Assessment					
Dimension 9: Skills & Competence					
Concerning the items listed below, how would you rate your degree of knowledge and expertise?					
Maturity Level / **Skills/ Knowledge**	**Unaware**	**Informed**	**Some Trained**	**All Trained**	**Expert**
Q 19) Agriculture Primary processes (e.g., Crop planning, Planting, Growing, Harvesting, Packaging, and sorting)	1	2	3	4	5
Q 20) Lean Production Methods (e.g., process mapping, Value Stream Mapping, waste elimination, etc.)	1	2	3	4	5
Q 21) Integrated Pest Management (IPM)	1	2	3	4	5

C. Skill and Knowledge Assessment					
Dimension 9: Skills & Competence					
Concerning the items listed below, how would you rate your degree of knowledge and expertise?					
Skills/ Knowledge \ **Maturity Level**	**Unaware**	**Informed**	**Some Trained**	**All Trained**	**Expert**
Q 22) Precision Agriculture (e.g., monitoring technology, sensors, robots & autonomous equipment, cameras, GPS, automatic irrigation, etc.)	1	2	3	4	5
Q 23) Data Analytics Techniques (e.g., Excel analytic tools, Minitab, Machine Learning)	1	2	3	4	5
Q 24) Simulation of the processes in the Greenhouse (e.g., systems simulation, digital twins, etc.)	1	2	3	4	5

Table 17: Scores and description of the Technology Capability dimension

D. Technology Assessment		
Dimension 10: Technology Capability		
Q 25) How would you rate the degree of technology incorporated into your Greenhouse operations?		
Options	**Definition**	**Scores**
◯	**The processes are not automated, and humans execute all Greenhouse processes.**	1
◯	**Humans execute Greenhouse processes with the assistance of basic automation.** (e.g., digital temperature, CO_2, and humidity measuring, smart lighting, automated irrigation, online ordering, etc.)	2
◯	**The processes are partially automated with significant human intervention.** (e.g., sensors monitor environmental conditions and alarm staff if the condition is out of criteria, smart devices help to identify pests and their intensity, using QR codes for inventory management and tracking process's execution, etc.)	3
◯	**The processes are almost automated with minimal human intervention.** (e.g., automated material ordering based on inventory level, automated resource planning, real-time process monitoring, using robots to do processes, real-time logistics, and condition tracking)	4
◯	**Digital simulation is used to improve performance and efficiency and test what-if scenarios.**	5

D. Technology Assessment
Dimension 10: Technology Capability
*If possible, please list the technologies currently implemented and used in the Greenhouse. - - -

Q 26) You will receive your Greenhouse technology maturity assessment results.

Would you then be willing to answer the following question? ◯ **Yes** ◯ **No**

Table 18: Result Evaluation Questions

Result Evaluation Questions		
Please provide your responses to the following questions based on your Greenhouse's maturity assessment findings.		
#	**Description**	**Response**
Q 1)	**How strongly do you feel the current technology ecosystem in your Greenhouse is helping you meet your business objectives and targets?**	◯ Strongly agree. ◯ Somewhat agree. ◯ Neutral. ◯ Somewhat disagree. ◯ Strongly disagree.
Q 2)	**To what extent can adopting more advanced technology than you already employed help you achieve your objectives (e.g., increased process effectiveness and average yield, improved product quality, etc.)?**	◯ Excellent ◯ High ◯ Medium ◯ Low ◯ None
Q 3)	**If you already know which technologies, please specify them; if not, describe what assistance you require from future technology adoption.**	- - - - -

Result Evaluation Questions		
Please provide your responses to the following questions based on your Greenhouse's maturity assessment findings.		
#	**Description**	**Response**
Q 4)	**How helpful were the results of the maturity assessment in helping you comprehend the current advanced technologies maturity status of your Greenhouse and assist you in developing a plan to successfully transition from traditional Greenhouse agriculture to lean and smart Greenhouse agriculture?**	○ **Strongly agree** ○ **Somewhat agree** ○ **Neutral** ○ **Somewhat disagree** ○ **Strongly disagree**
Q 5)	**Is any other information that was not touched on that is essential to include? If no, enter "n/a."**	

3.3.4.4. Digital Twin-Value Stream maturity assessment procedure

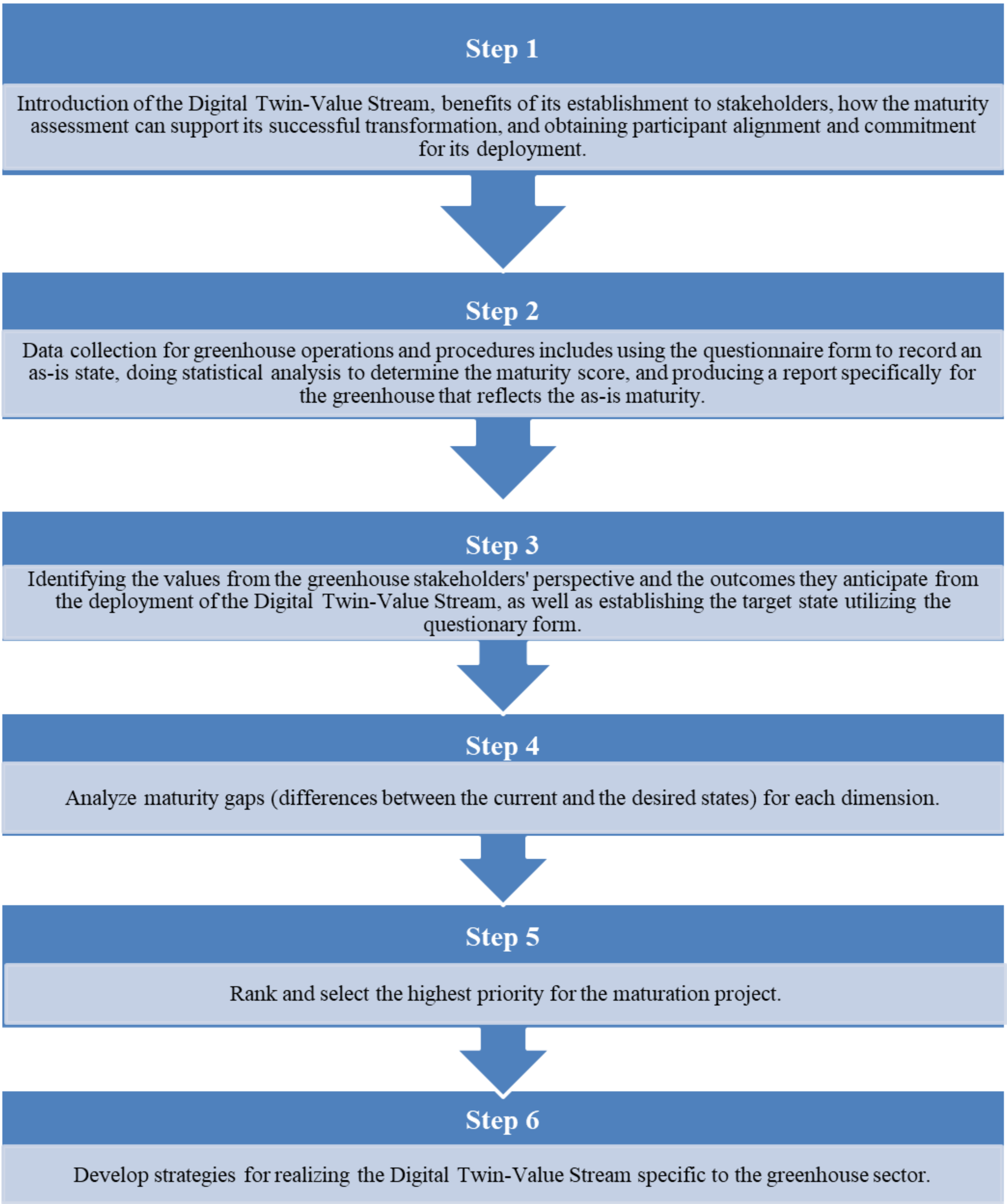

Figure 18:DT-VS maturity assessment procedure for Greenhouses inspired by (Schumacher, Nemeth and Sihn, 2019)

3.3.4.5. Maturity Score Calculation

To comprehend the current maturity level, selecting the best strategy to adopt in order to attain higher maturity, prioritize those strategies in order to fulfill their short- and long-term goals, and obtain the greatest outcomes for the least amount of money and effort, each Greenhouse must calculate not only its overall maturity score but also the maturity scores of each dimension and its corresponding building block. Therefore, the maturity score calculation of specific dimension, building block and the overall maturity score (MS_O) of the Greenhouses appropriately established, inspired by (Wagire *et al.*, 2021; Fenton, 2022) study.

The developed maturity assessment model has 'i' building block and 'j' maturity dimensions. The maturity level of a certain dimension, as determined by assessing each Greenhouse in that particular dimension, corresponds to the maturity score for that dimension. The following formula is used to compute each dimension's maturity score:

Equation 1: $D_j = W_j * S_j$

Where:

D_j= Maturity Score for Dimension j, And j=1,2,…,10

W_j= Dimension j Weighting Factor

S_j= Given Score for Dimension j, *

*** The average score of the answers will be considered if each dimension has more than one question.**

Equation 2: $BB_i = \sum_{j=1}^{n} D_j$

Where:

BB_i= Maturity Score for Building Block i, And i=1, 2, 3, or 4

D_{ji}= Maturity Score for dimension j in Building Block **i**,

n= Latest dimensions in Building Block **i**

The overall maturity score (MS_O) for the Greenhouse under consideration is calculated using the following equation:

Equation 3: MSO = $\frac{\sum_{i=1}^{n} W_i * BB_i}{\sum_{i=1}^{n} W_i}$

Where:

MSO = Overall Maturity Score, $1 \leq MSO \leq 5$

W_i= Building Block i Weighting Factor, i=1, 2, 3, 4

These calculated maturity scores are then utilized to understand the Greenhouse's readiness for DT-VS development and establish a technology adoption strategy to reach the targeted state. The maturity scores and accompanying maturity levels are broken down in Table 19.

Table 19: Overall Maturity Score versus Maturity Level

Overall Maturity Score	Maturity Level
$1 \leq MSO < 1.5$	Level 1: Traditional Greenhouse
$1.5 \leq MSO < 2.5$	Level 2: Basic
$2.5 \leq MSO < 3.5$	Level 3: Intermediate
$3.5 \leq MSO < 4.5$	Level 4: Advanced
$4.5 \leq MSO \leq 5$	Level 5: Smart Lean Greenhouse

3.3.4.6. Dimension Prioritization Strategy

For this study, we sort the results and make the following assumptions for prioritizing the dimensions. However, there are several prioritization techniques that can be used in future studies, such as sorting, AHP, Pugh Matrix, MoSCoW, etc.

Table 20: Dimension Prioritization Strategy

Priority	Prioritizing Strategy
1st	The lowest score or the biggest gap (assuming its prerequisites have matured enough, if not, the dimension that logically is one of the most fundamental demands before the dimension with the lowest score or the biggest gap can upgrade)
2nd	Identical Dimension Score, Free Selection of Either (considering their interdependencies and logical relationships)

3.3.4.7. DT-VS Implementation Strategy

Once our maturity assessment model is developed, we use it to assess the maturity level in the Greenhouse. If there is a discrepancy between what is needed and what is there, we develop an improvement strategy to address the shortcomings and repeat this cycle, figure 19, until the target is achieved. At the same time, we are actively searching for more effective approaches, and we can advance our maturity assessment model by utilizing the feedback we receive from the implementation strategy and market updates.

Figure 19: DT-VS Implementation Strategy

CHAPTER 4- USE CASE, CASE STUDIES AND RESULTS

4.1. Overview

It is important to evaluate a model's effectiveness after designing it. Therefore, to ensure the formula employed in the model is accurate, it can be tested by a pilot of data generation, also known as a use case, before being published and put into implementation. The research's hypothesis can then be evaluated for acceptability using a real-world case study, and any improvements can be made in light of the feedback.

4.2. Use Case

The proposed model should be examined before being used, as was previously stated, to ensure its validity. Instead of putting it into practice in the real world for this reason, it can be tested with a variety of randomly generated data in a Use Case scenario, and the outcomes can then be assessed for the accuracy of the model and formula.

4.2.1. Generating Data

The first step, which is the generation of random data, can be accomplished in a variety of methods, the simplest of which is to produce these random numbers using Excel. The table below, table 21, shows one set of the random data that Excel generated, using the formula "=RANDBETWEEN (bottom, top)", for each of the dimensions.

Table 21: Data Generation for the Use Case

# BB	Building Block (BB)	Dimension Name (D)	Dimension Score
1	Business Structure Assessment	Vision	3
		Culture	4
		Risk Management Approach	1
		Decision-Making Approach	3
2	Processes Assessment	Production Processes	2
		Crop Protection Processes	3
		Value Chain Processes	2
		Process Integration	2
3	People Assessment	Skills & Competence	3
4	Technologies Assessment	Technology Capability	3

4.2.2. Digital Twin-Value Stream Maturity Assessment of the Use Case

Once the data is generated, the next step is to use the formulas introduced in the previous section, D.II and D.V, for the maturity assessment. Therefore, based on the proposed formula, we will calculate the scores of each dimension, building block, and overall maturity. The results are given in table 22.

Table 22: Use Case Maturity Score Calculation

# BB	Building Block (BB i)	BB WF	Dimension (Dj)	BB Total Dimensions	Dimension WF	Dimension j Given Score	Dimension Maturity Score	BB Maturity Score	Overall Maturity Score
1	Business Structure Assessment	0.25	Vision	4	0.25	3	0.75	2.75	2.75
			Culture		0.25	4	1.00		
			Risk Management Approach		0.25	1	0.25		
			Decision-Making Approach		0.25	3	0.75		
2	Processes Assessment	0.25	Production Processes	4	0.25	2	0.50	2.25	
			Crop Protection Processes		0.25	3	0.75		
			Value Chain Processes		0.25	2	0.50		
			Process Integration		0.25	2	0.50		
3	People Assessment	0.25	Skills & Competence	1	1.00	3	3.00	3.00	
4	Technologies Assessment	0.25	Technology Capability	1	1.00	3	3.00	3.00	

Also, Using Excel's graph function, we will draw the radar chart, figure 20, to outline the current maturity of the use case at a glance.

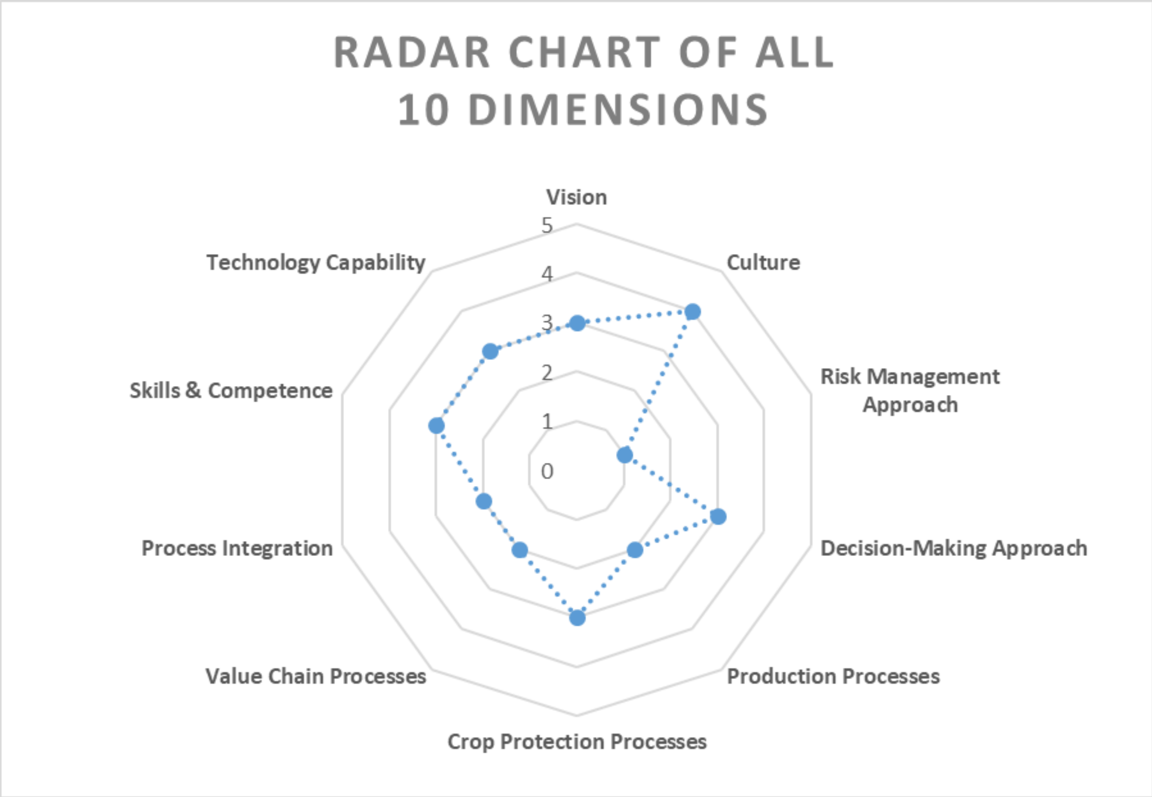

Figure 20: Radar Chart of Dimension Scores for the Use Case

4.2.3. Maturity Assessment Analysis and Results for the Use Case

The overall maturity score obtained from the maturity assessment concludes that the maturity level of the use case is at level 3, which is the Intermediate level. We should prioritize the dimensions by considering a variety of contributing factors, such as importance, lack of maturity, cost and required resources, and the structure of the case under study, after learning about the current state of the use case and its shortcomings. Then, develop a strategy for promoting those prioritized dimensions to a higher maturity level.

The next table, table 23, illustrates the dimension's prioritization for this use case based on the previously discussed dimension prioritizing strategy.

Table 23: Use Case Dimension Prioritization

# BB	Building Block (BB)	Dimension (D)	Dimension Weight	Dimension Maturity Score	BB Maturity Score	Dimension Priority
1	Business Structure Assessment	Vision	0.25	0.75	2.75	5
		Culture	0.25	1.00		8
		Risk Management Approach	0.25	0.25		1
		Decision-Making Approach	0.25	0.75		6
2	Processes Assessment	Production Processes	0.25	0.50	2.25	2
		Crop Protection Processes	0.25	0.75		7
		Value Chain Processes	0.25	0.50		3
		Process Integration	0.25	0.50		4
3	People Assessment	Skills & Competence	1.00	3.00	3.00	9
4	Technologies Assessment	Technology Capability	1.00	3.00	3.00	10

The author chose the top three priorities for further implementation strategy development based on the results of the dimensions' priority. Table 24 provides the developed implementation strategy for this use case by the author.

Table 24: DT-VS Maturity Assessment Implementation Strategy for Technology Adoption in Greenhouses

Priority	Dimension	Dimension Given Score	Targeted Score	Implementation Plan
1st	Risk Management Approach	1	3	For this Use Case, there is no risk mitigation or contingency plans. The first step is to identify all events that can negatively affect the objectives of the Greenhouse using a risk matrix. The tools that help determine the risks are 1. analyzing existing documentation, 2. interviewing with experts, 3. conducting brainstorming meetings, 4. using existing standard methodologies like FMEA, causes trees, etc., 5. considering the lessons learned from previous crop cycles or other Greenhouses. Then identify the occurrence probability and impacts severity and calculate the risk score. Based on the score and further consideration like budget, importance, existing skills and resources, develop risk prevention like IPM program and risk response strategies. Routinely monitor the condition and modify the strategy if needed.
2nd	Production Processes	2	3	Define all production processes, their sequence, needed resources and conditions, cycle time, etc., visualize the processes and procedures for employees and train them, and develop the SOPs for every single process. Also, develop a plan for carrying out the processes and assign proper staff and resources. Set performance metrics for all processes and define the intervals for evaluating the process efficiency by monitoring them and comparing those performance metrics and looking for technologies that can help process improvement and apply some of the lean manufacturing principles to reduce process waste.
3rd	Value Chain Processes	2	4	Identify and document all existing Suppliers, Inputs, Processes, Outputs, Costumer of the Greenhouse, all services and products they receive from their suppliers and provide to their customers, collect critical information like lead time, price, cost, logistics method, order interval, etc. map the value stream to find out possible bottlenecks and wastes. Identify technologies to help improve those wastes and reduce their value chain cost to enhance the net profit.

4.3. Case Study: DT-VS Maturity Assessment for Greenhouse Agriculture Sector in Windsor-Essex, Canada

After the model was validated using the Use Cases and generated data, the developed DT-VS maturity assessment model in this study was employed in Windsor-Essex, Canada's Greenhouse Agriculture sector, to verify model validation in the real world. Ten greenhouses (out of 25 requested) in southern Ontario completed the questionnaire. The interviewees included CEOs or crop scouts of greenhouses, which were willing to participate in this research and provide their data. This questionnaire was conducted in various Greenhouses with different kinds of products to ascertain the general maturity stage of technology adoption and process management in the Greenhouse agriculture sector. Small Greenhouses are those with fewer than 10 acres, medium-sized are those with around 25 acres, and large Greenhouses are those with more than 50 acres. The overall maturity of each Greenhouse was then determined by analyzing the collected data using a mathematical equation.

4.3.1. Data Collection

Table 25 presents the scores given to various dimensions based on how the interviewees from different Greenhouses responded to the questionnaire. As mentioned before, the average score of the responses was considered for dimensions with several questions.

Table 25: Greenhouses Data Collection

Greenhouse	Size	Product	Dimension given score									
			1	2	3	4	5	6	7	8	9	10
A	Medium	Cucumber	2	4	4	4	2	2	2	2	2	2
B	Medium	Tomato	1	3	3	4	2	2	2	2	3	2
C	Large	Cucumber, Tomato, Strawberries	4	4	3	4	3	3	4	4	3	2
D	Medium	Cucumber	2	2	2	4	3	2	5	4	3	4
E	Large	Cucumber	3	4	3	4	3	3	3	2	3	3
F	Medium	Tomato	2	4	2	4	3	4	2	2	3	2
G	Large	Tomato, Strawberries	2	5	3	4	3	3	3	2	3	3
H	Medium	Strawberries	4	4	3	4	3	3	3	3	3	2
I	Large	Pepper	5	5	4	4	4	4	3	3	3	3
J	Small	Cannabis	2	3	2	4	4	3	2	2	3	1

4.3.2. Maturity Assessment Analysis and Results

Once data from the greenhouses had been gathered, their corresponding overall maturity score was calculated using equation 1 to determine how well each greenhouse is currently managing its processes and utilizing advanced technology to support those processes. The greenhouses were then contrasted against one another based on their building block, dimension level, and overall maturity score. Table 26 illustrates the overall maturity score of each Greenhouse and the maturity level corresponding to that score.

Based on the average of all ten sample greenhouses' overall maturity scores, the greenhouse agriculture sector, within the scope of this research, has a maturity level score of three, and the maturity level corresponding to that number is intermediate. It means Greenhouse suppliers, inputs, processes, outputs, and costumers are clearly defined. Greenhouse production processes and crop protection processes are defined and documented but need to be standardized. Processes are regularly planned based on how urgently they need to do them and resource availability. The lack of resources may force the withdrawal or change the order of some processes. Value chain processes are managed based on top priority factors (e.g., suppliers' lead time, quality, price, etc.). Some processes are carried out based on SOPs and sometimes are checked by physical observation or smart devices like QR code readers to evaluate their efficiency and adherence to SOPs. Some lean manufacturing principles and tools are employed to reduce/ eliminate process wastes (e.g., motion, over-processing, handling) and improve them. The processes are partially automated with significant human intervention, and all internal processes are formally linked. Short- and long-term plans for improving Greenhouse processes and utilizing technology to support and facilitate process improvement are defined and conveyed to staff members and other stakeholders, the timeline is set, and proper funding and resources are allocated. Greenhouse's daily and managerial decisions are based on awareness and knowledge obtained from research and reviewing scientific information. Growers strive to lessen the degree and likelihood of pest harm by engaging in several activities, like Integrated Pest Management (IPM). Their strategy for addressing Greenhouse risks is the preventive approach. Some Greenhouse staff and stakeholders are trained to conduct Greenhouse agriculture processes efficiently and employ adopted technologies. They accept changes in principle, like technology adoption or process optimization, but they have not yet committed.

Table 26: Overall Maturity Score of the Greenhouses in Windsor

Greenhouse	Size	Product	Overall Maturity Score	Maturity Level
A	Medium	Cucumber	2.38	Level 2: Basic
B	Medium	Tomato	2.44	Level 2: Basic
C	Large	Cucumber, Tomato, Strawberries	3.06	Level 3: Intermediate
D	Medium	Cucumber	3.25	Level 3: Intermediate
E	Large	Cucumber	3.06	Level 3: Intermediate
F	Medium	Tomato	2.69	Level 3: Intermediate
G	Large	Tomato, Strawberries	3.06	Level 3: Intermediate
H	Medium	Strawberries	2.94	Level 3: Intermediate
I	Large	Pepper	3.50	Level 4: Advanced
J	Small	Cannabis	2.38	Level 2: Basic

Figure 21 shows a visualization of the overall maturity score for each participating Greenhouse using a radar chart. According to figure 22, 60%, or six out of ten selected Greenhouses, are at the intermediate level and 30% at the basic level. As a result, there is plenty of opportunity for process improvement in this sector.

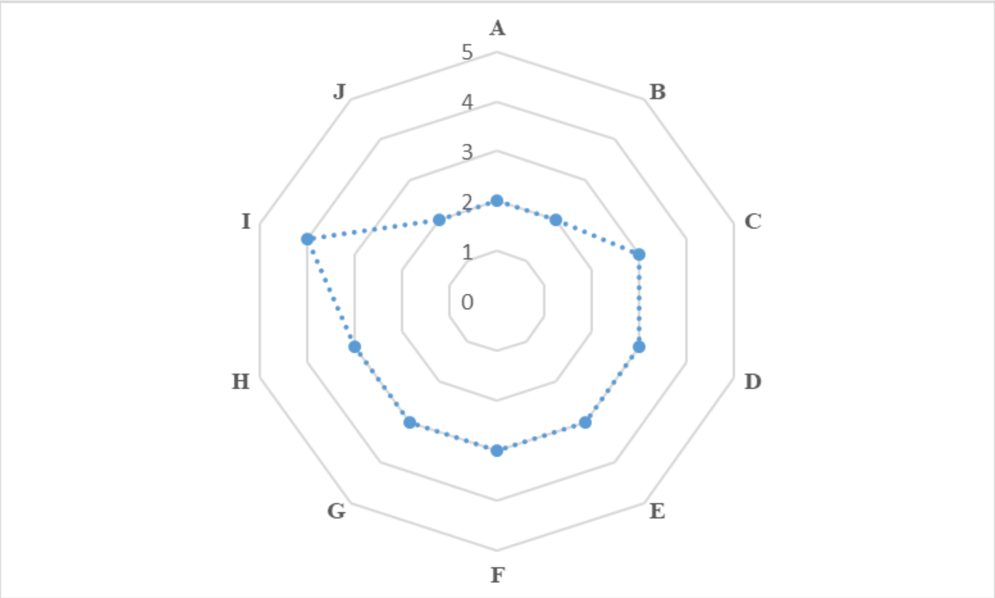

Figure 21: Overall Maturity Score for each Greenhouse

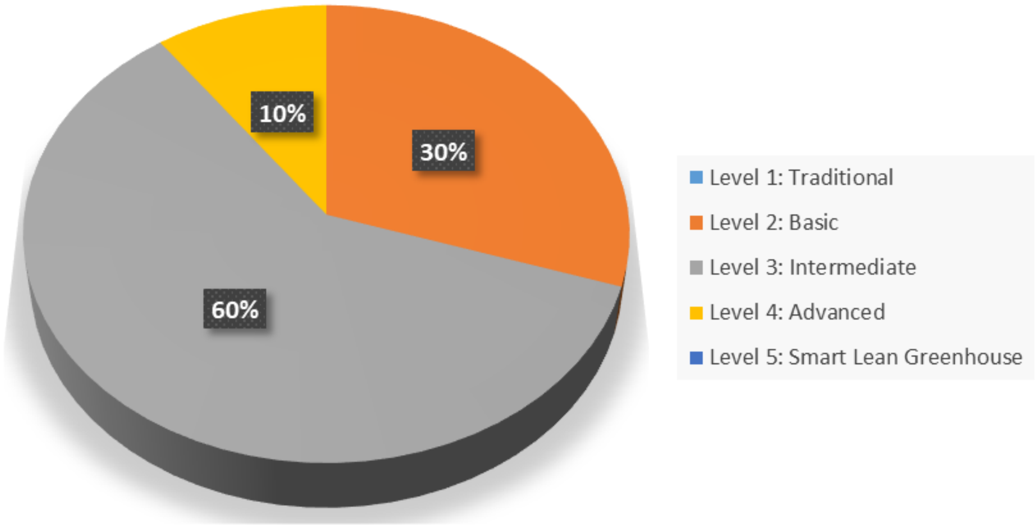

Figure 22: Comparing the Overall Maturity Level of Different Greenhouses

When we compare the results of the various Greenhouses' building blocks, figure 23 shows that most of them carry out their processes with fundamental technology and with insufficient staff training, resulting in inefficient process management.

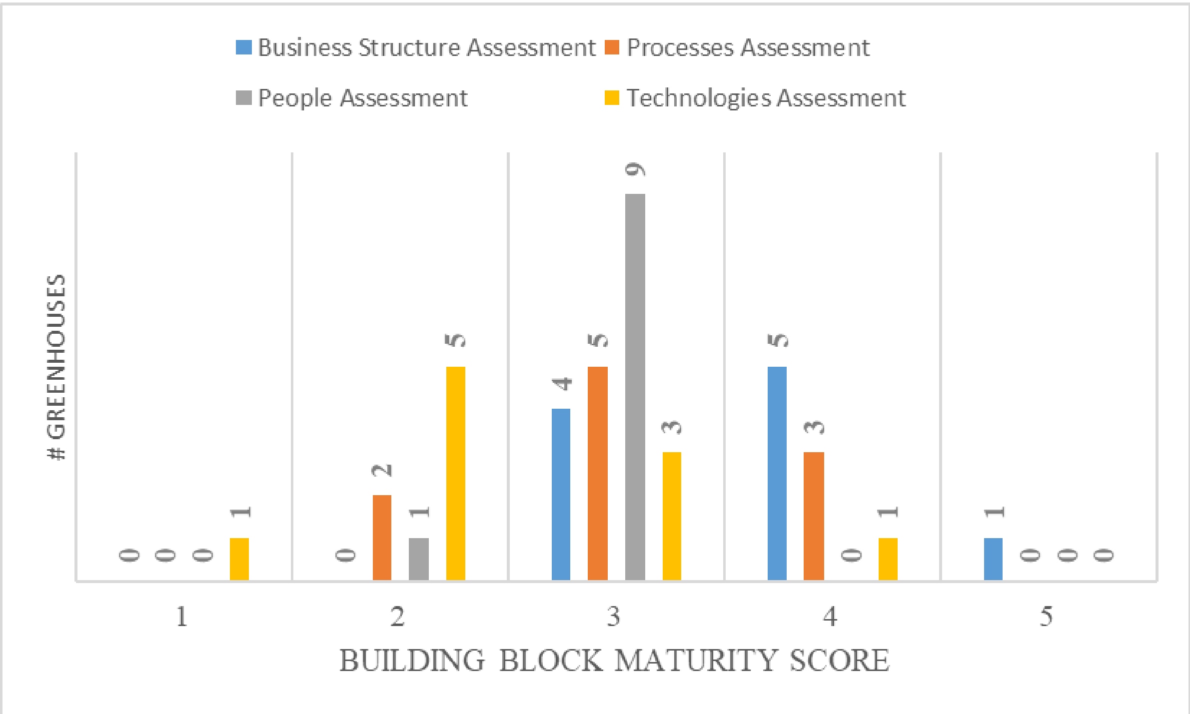

Figure 23: Comparing the Maturity Scores of Various Building Blocks in Selected Greenhouses

We now turn to each building block separately and investigate them in more detail by comparing their associated dimensions and how each Greenhouse responded to them to develop a strategy that would benefit this sector.

Business structure assessment, which is the first building block, has four dimensions: 1. vision, 2. culture, 3. risk management strategy, and 4. decision-making strategy. The responses of each Greenhouse to each dimension subset of this building block are shown in a radar chart, figure 24.

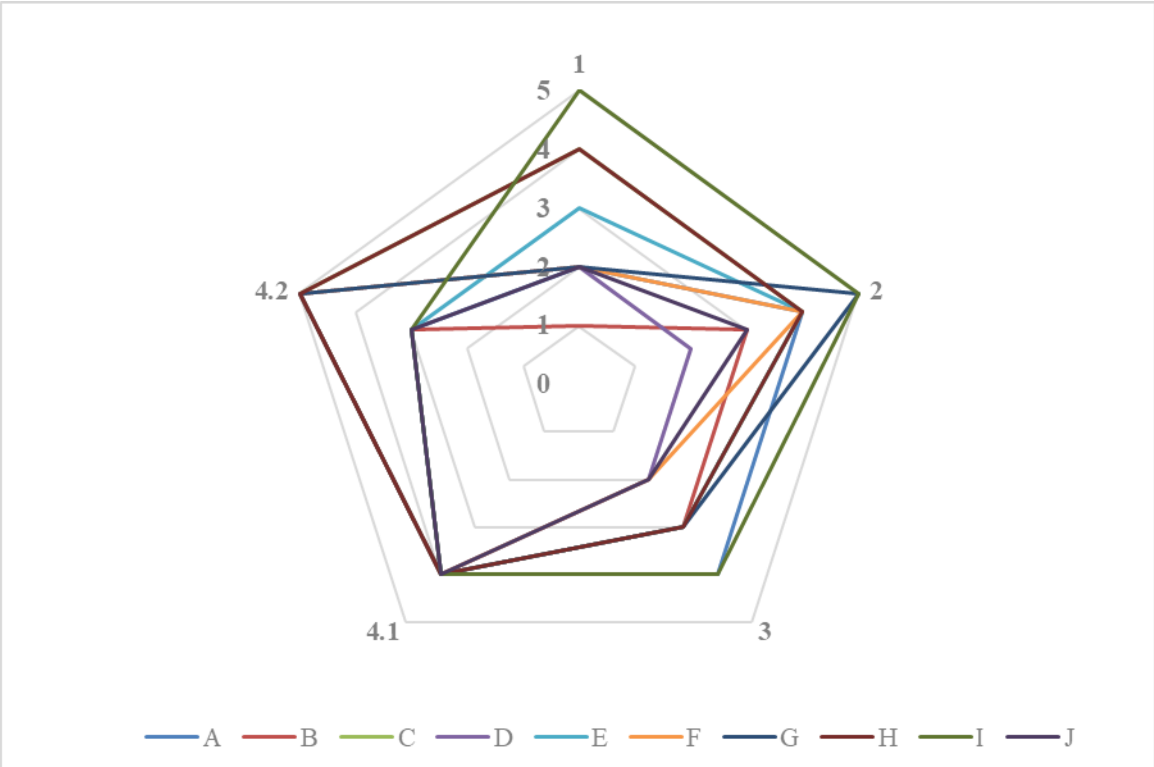

Figure 24: Building Block 1 and Associated Dimensions

The first dimension, vision, is interested in the goals established for Greenhouses concerning strengthening Greenhouse processes and leveraging technology to support and facilitate process enhancement. The survey's findings, figure 25, reveal that roughly 50% of Greenhouses are at the "Basic Level," where short- and long-term plans are defined and clearly communicated to workers and other stakeholders. Still, many of them have not yet been put into action. Therefore, we should assist them in identifying the causes of not carrying out their plans.

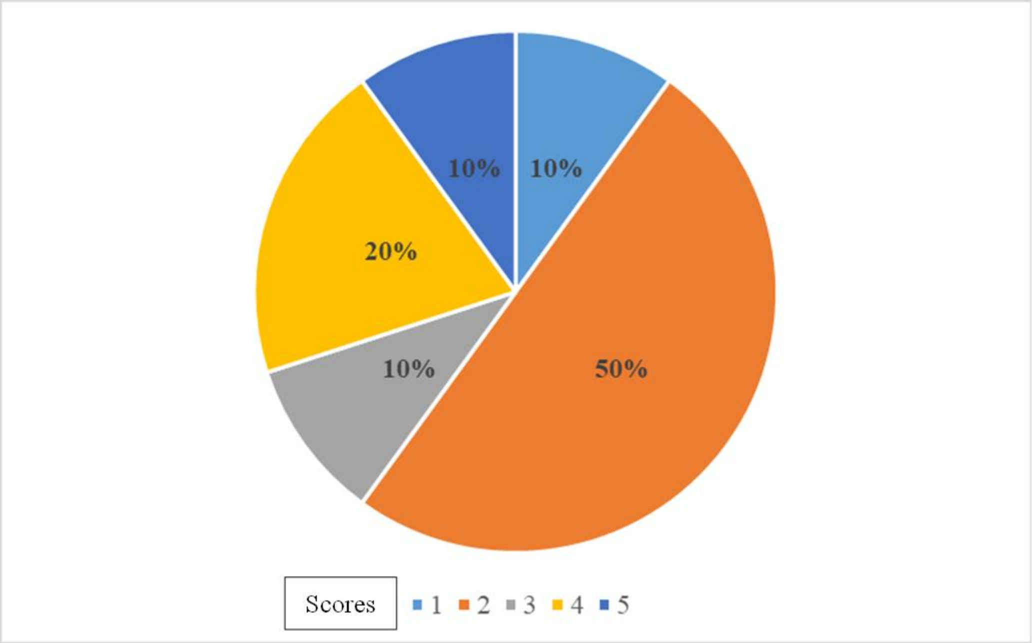

Figure 25: Responses to the Dimension 1 Questions

The second dimension, culture, is interested in the adaptability of Greenhouse staff and stakeholders toward new ideas or future changes for improvement. The survey's findings, figure 26, reveal that roughly 50% of Greenhouses are at the "Advanced Level," where Greenhouse staff and stakeholders understand the value of changes and try to incorporate them into their daily activities, which is a sufficient level and does not require upgrading as a top priority.

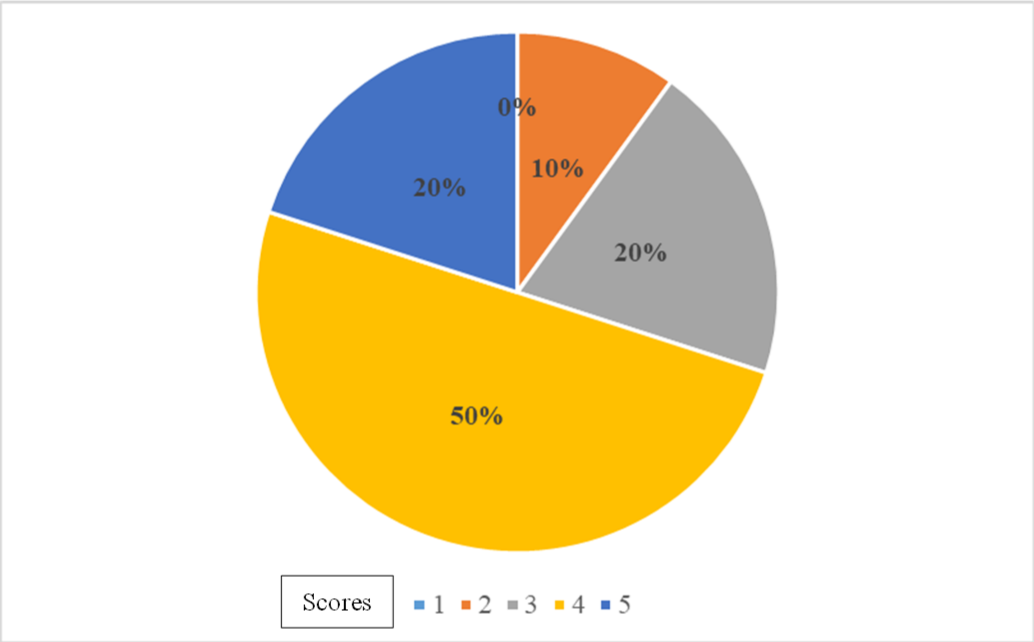

Figure 26: Responses to the Dimension 2 Questions

The risk management approach, the third dimension, is concerned with the degree of addressing Greenhouse risks and has a strategy for dealing with them. The survey findings in figure 27 reveal that roughly 50% of Greenhouses are at the "Intermediate Level," where some Greenhouses take a preventative strategy while others perform at a lower level. As a result, we must first help Greenhouses at a lower level identify their risks and take steps to at least be preventive. Then we need to provide them with the tools they need to take higher levels of risk management approaches.

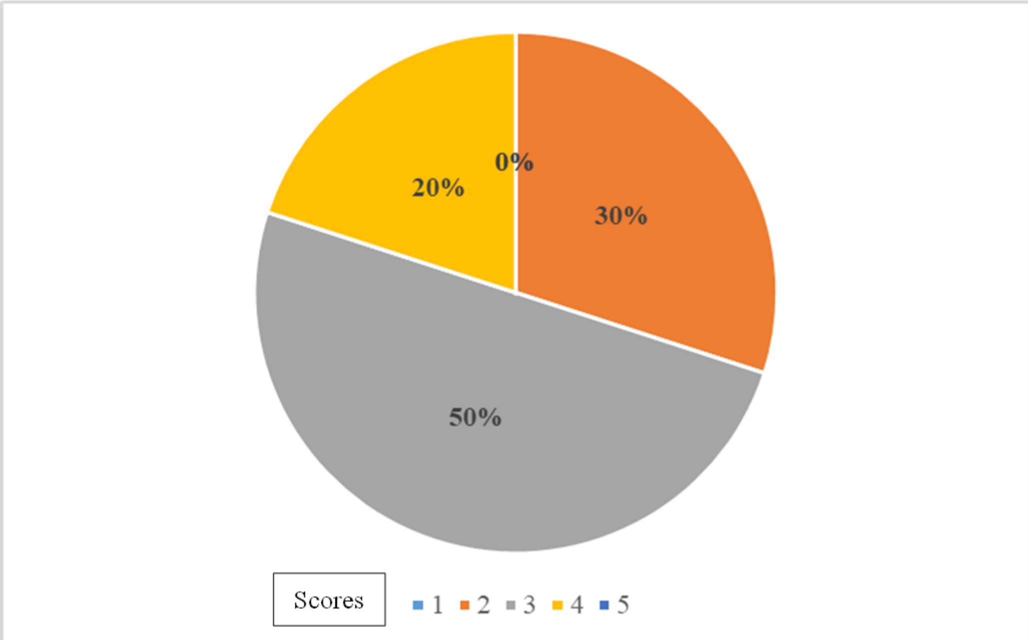

Figure 27: Responses to the Dimension 3 Questions

The fourth dimension is the decision-making approach concerned with the maturity level in managerial and day-to-day Greenhouse decisions. Figure 28 of the survey's result shows that practically all Greenhouses are at the "Advanced Level," where they use some form of data analysis on their historical data that is currently available, even though most of them use straightforward tools like Excel for such analysis and do not have all the data that should be considered. However, without technology, humans cannot employ a wide range of criteria to make decisions. Moreover, to utilize these technologies for accurate decision-making, certain infrastructures are needed, including the availability and collection of precise information about the processes, the existence of standards and parameters that can be used to check the effectiveness of the processes, the skill to use the technologies, investment in them, and so on. We will thus address the enhancement of these dimensions once the required infrastructure is in place. The data being gathered to support daily and management choices in the investigated greenhouses include the following based on questionnaire responses: environmental conditions (like temperature, RH, CO2, humidity), working hours, scouting results, irrigation, and water analysis, yield, or production per box.

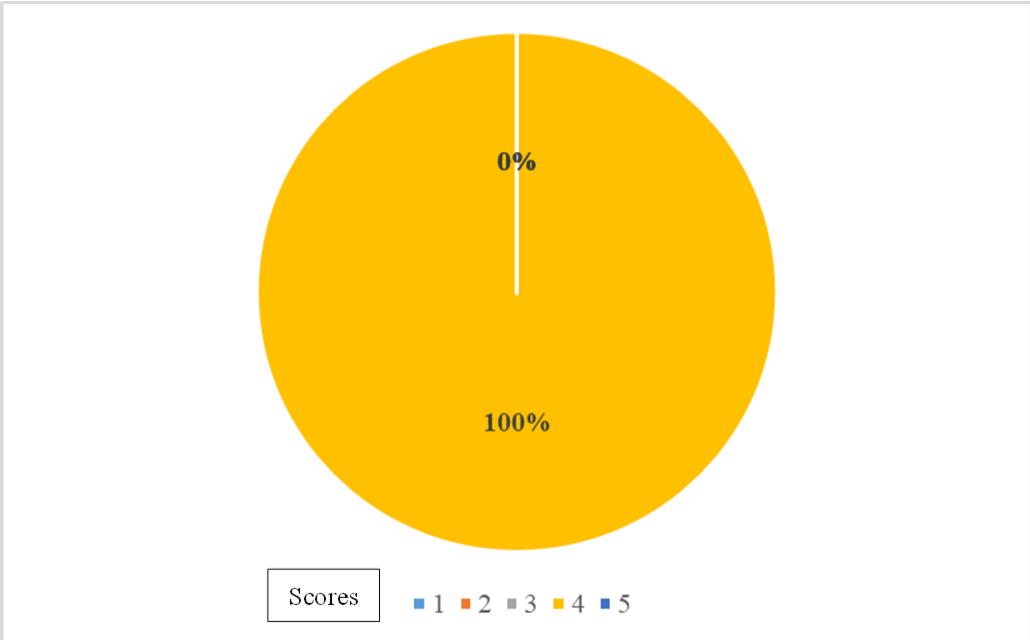

Figure 28: Responses to the Dimension 4 Questions

The second building block discussed in this study is Process Assessment which includes four dimensions: 1. production processes, 2. crop protection processes, 3. value chain processes, and 4. process integration. The responses of each Greenhouse to each dimension subset of this building block are shown in the following radar charts, figures 29 and 30.

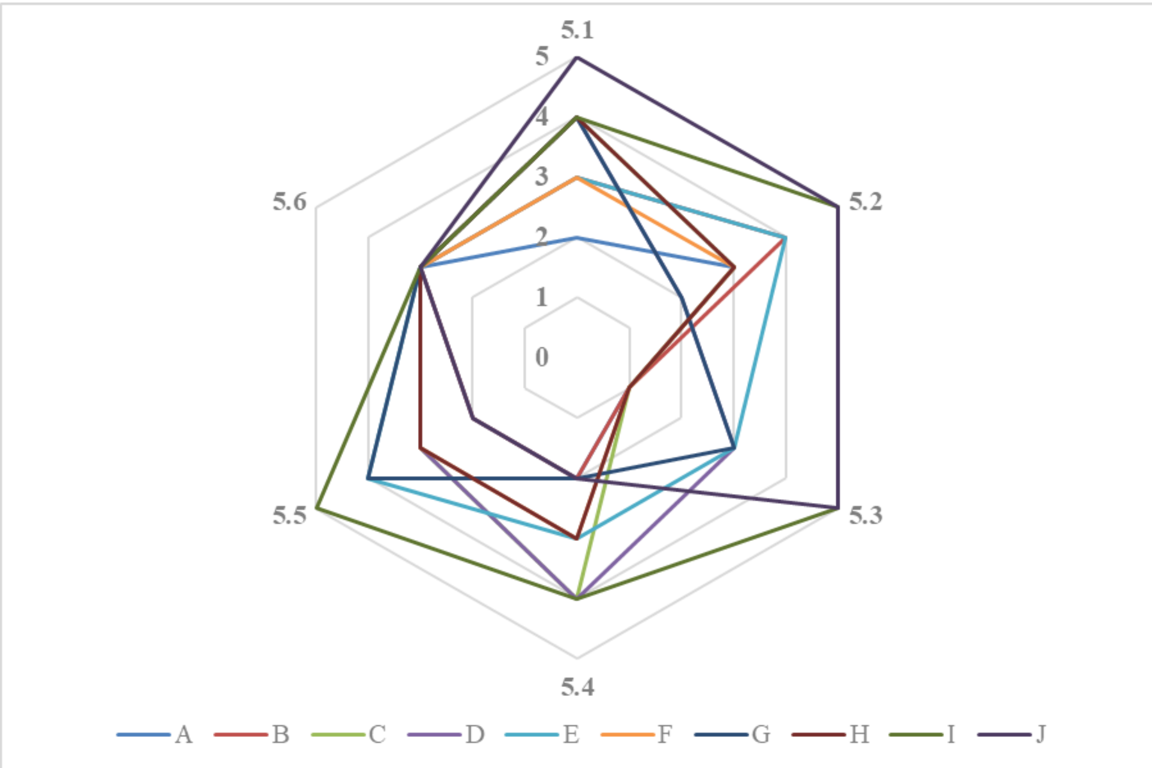

Figure 29: Building Block 2, Production Processes Dimension

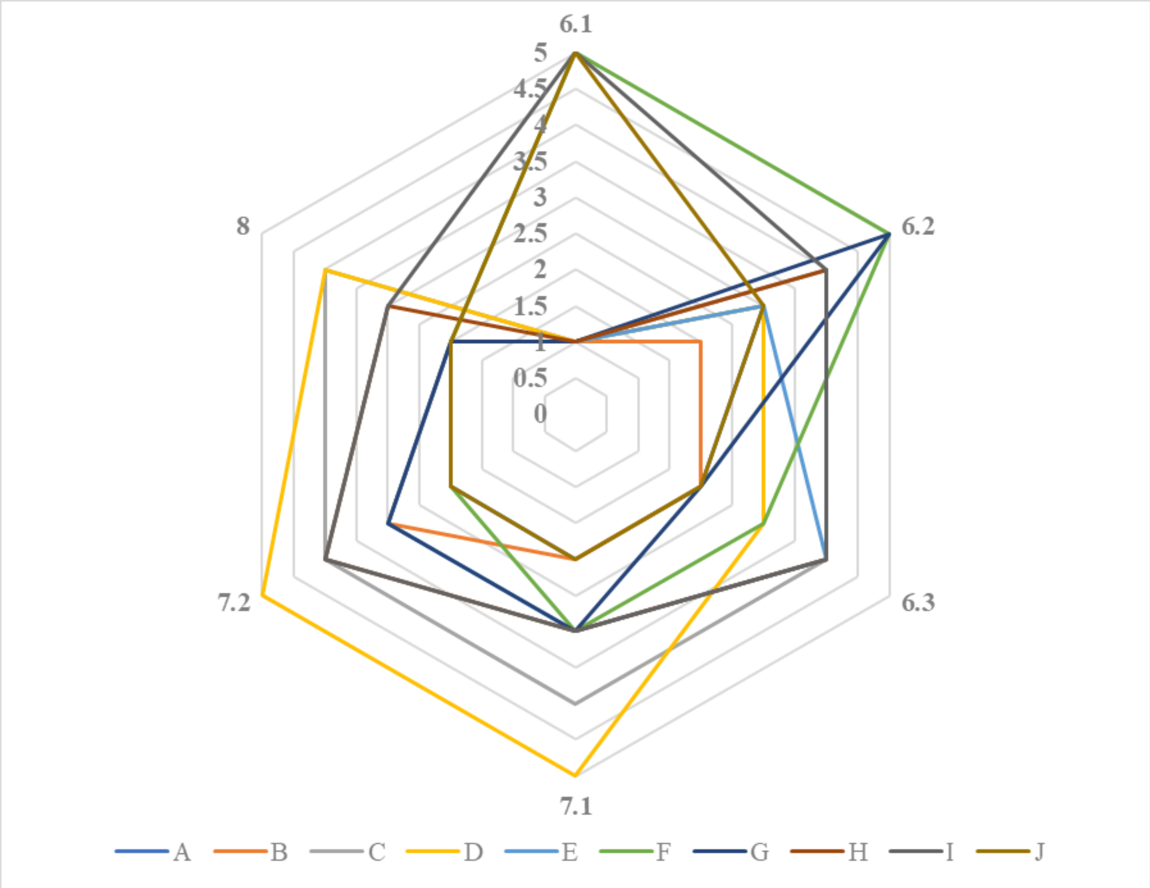

Figure 30: Building Block 2, Other Associated Dimensions

The fifth component, production processes, concentrates on how successfully Greenhouse production processes are defined, planned, carried out, and evaluated for efficiency regularly. They also inquired how much of the lean manufacturing idea they had adopted to improve their processes. The survey's findings, in figure 31, reveal that roughly 60% of Greenhouses are at the "Intermediate Level," where their processes are defined and recorded but not yet standardized. At this level, Greenhouses regularly plan their processes based on how urgently they are needed, and a lack of resources may force them to withdraw from or reorder some processes. They carried out their processes primarily based on their experience, but some were based on available SOPs. They sometimes monitor and control their processes for efficiency, typically through observation, manual data collecting, or sporadic use of a smartphone or other smart device. Additionally, they have initiated implementing lean manufacturing principles and tools to decrease waste in their processes and enhance them. Despite having a higher average score than the other dimensions and possibly being one of the last priorities in the process of prioritization when the scores are sorted, this dimension, which is one of the most crucial and fundamental aspects of Greenhouse agriculture, must attain a level 5 in each of the subsections 5.1, and 5.3 and at least level 4 in 5.2, and 5.4. Other sub-sectors can be improved if the level of technology is raised in each greenhouse.

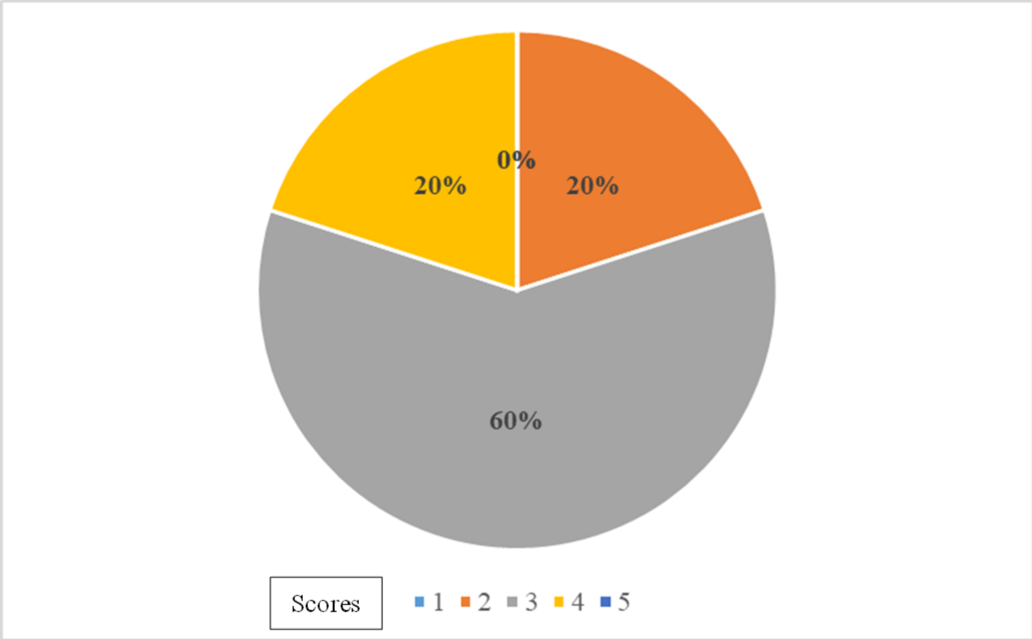

Figure 31: Responses to the Dimension 5 Questions

Crop protection processes are the other dimension which is one of the vital dimensions for Greenhouse agriculture. Numerous pests, such as bacteria, fungi, weeds, and insects, hurt agriculture, resulting in lower productivity and poor product quality. Growers should always watch for pest populations, beneficial species, and environmental conditions that can cause problems. The survey's findings, figure 32, reveal that roughly 50% of Greenhouses are at the "Intermediate Level," where their crop protection processes are defined and recorded but not yet standardized. At this level, Greenhouses regularly plan and carry out their processes based on how urgently they are needed, and a lack of resources may force them to withdraw from or reorder some processes. They sometimes monitor and control their crop protection processes for efficiency, typically through observation, manual data collecting, or sporadic use of a smartphone or other smart device. Due to its importance, this dimension has a vital priority and must attain level 5 in subsections 6.1 and at least level 4 in 6.2 and 6.3. It can later be promoted to a higher maturity level if the level of technology is raised in each greenhouse.

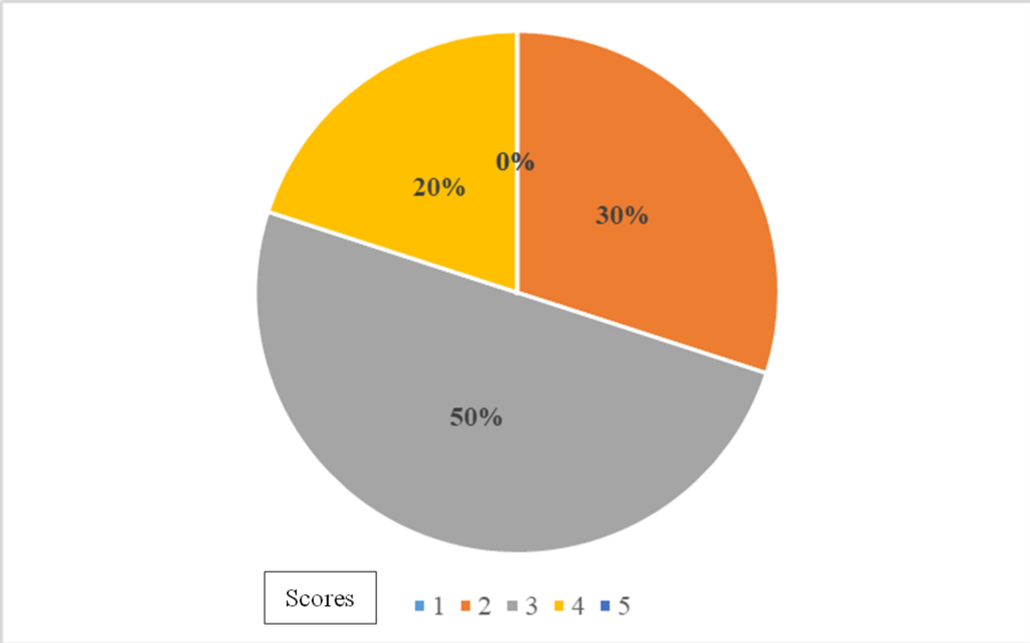

Figure 32: Responses to the Dimension 6 Questions

The value chain processes are the third component in the process assessment building block (dimension 7). Figure 33 of the survey's result shows that around 40% of Greenhouses are at the "Basic Level" and 40% are at the "Intermediate Level." At the basic level, their value chain processes are partially defined and poorly documented, and some are planned and carried out based on the price and availability of suppliers. At the intermediate level, all suppliers, inputs, processes, outputs, and costumer are properly defined, and usually, they are planned and carried out based on various critical factors. If the two preceding dimensions are not sufficiently developed and matured, this dimension will not be able to expand well. Thus, it would take priority once the other two had achieved sufficient progress, as previously specified.

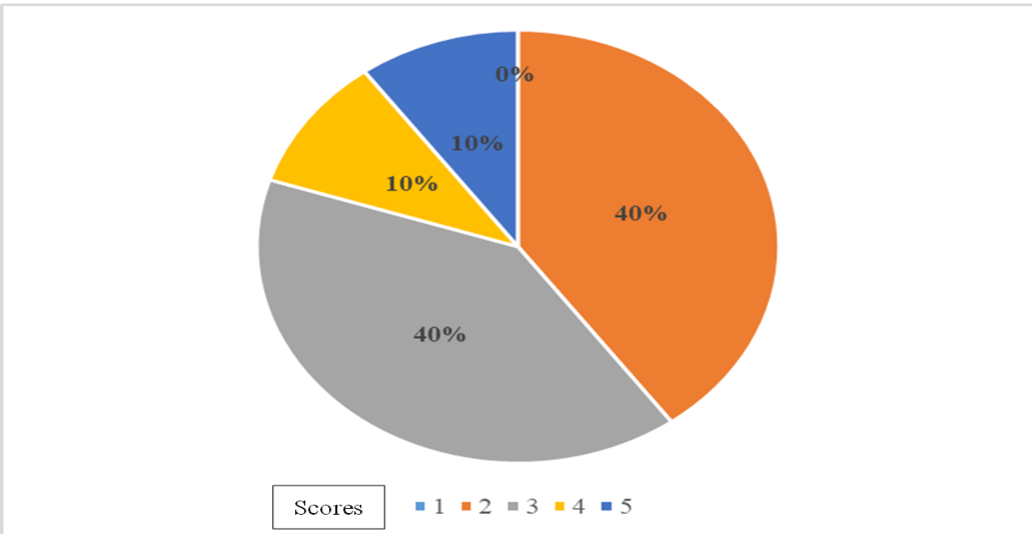

Figure 33: Responses to the Dimension 7 Questions

Integration of processes is the fourth dimension of this building block. Business processes that are not integrated waste resources and keep Greenhouse data in distinct silos, negatively impacting quality, performance, and profitability. The survey's findings, figure 34, reveal that roughly 60% of Greenhouses are at the "Basic Level," where only some processes are formally linked. There should be some technology infrastructure, like ERP, CRM, etc., to increase this dimension. Thus, it can later be promoted to a higher maturity level if the level of technology is raised in each of the Greenhouses.

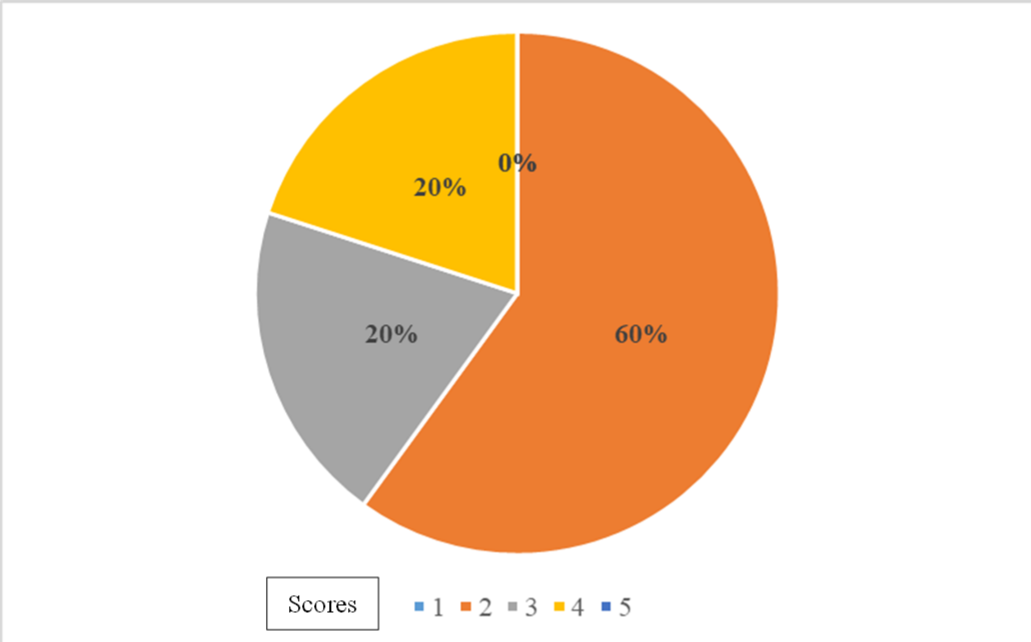

Figure 34: Responses to the Dimension 8 Questions

In this study, the third building block is called the Skill and Knowledge Assessment, which measures six skills and knowledge across one dimension, skills and competence: 9.1. Agriculture Primary processes, 9.2. Lean Production Methods, 9.3. Integrated Pest Management (IPM), 9.4. Precision Agriculture, 9.5. Data Analytics Techniques, and 9.6. Simulation of the processes in the Greenhouse. In a radar chart, figure 35, the responses of each Greenhouse to each subset of this building block are displayed. The survey's findings, figure 36, reveal that roughly 90% of Greenhouses are at the "Intermediate Level," where some employees have received training in these concepts and skills. It should be considered while planning for the improvement of this dimension that some of these sub-dimensions, like primary agriculture processes, have a high priority of progressing to at least level 4, while others, like a simulation of the processes in the Greenhouse, depend on the degree of technological adoption in the individual Greenhouses.

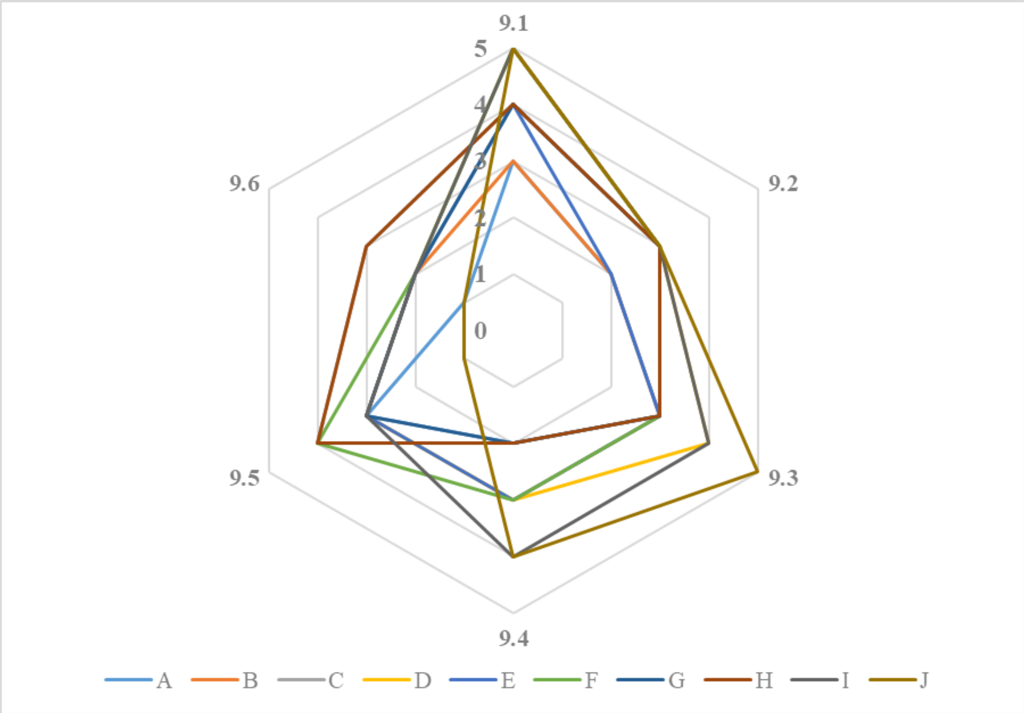

Figure 35: Building Block 3 and Associated Dimensions

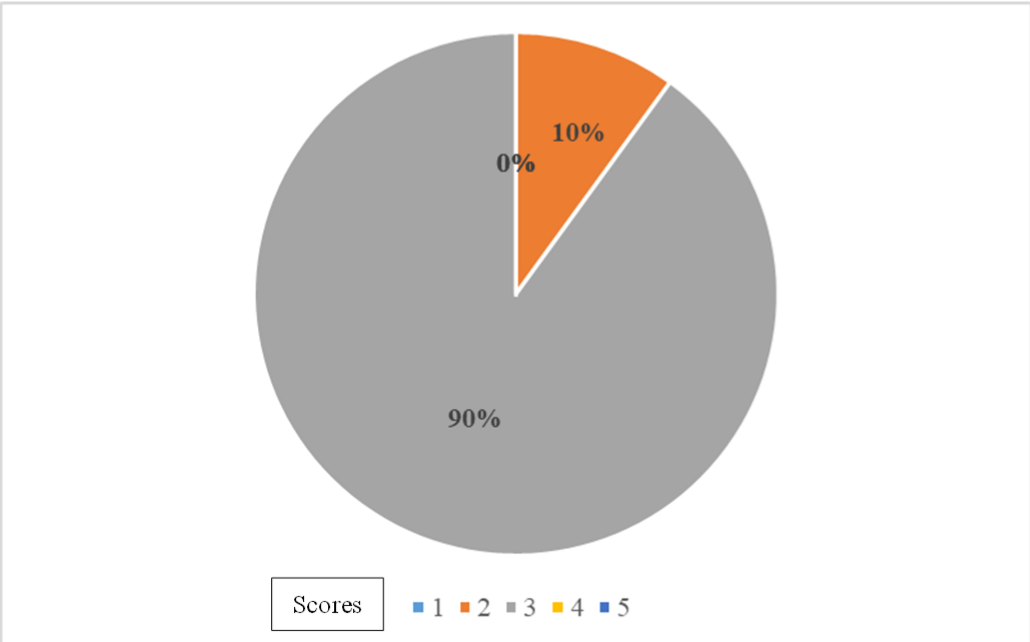

Figure 36: Responses to the Dimension 9 Questions

Technology Assessment and technology capability are the final building block and dimension of this study, respectively. A radar chart, figure 37, displays how each Greenhouse responded to this building block's dimension.

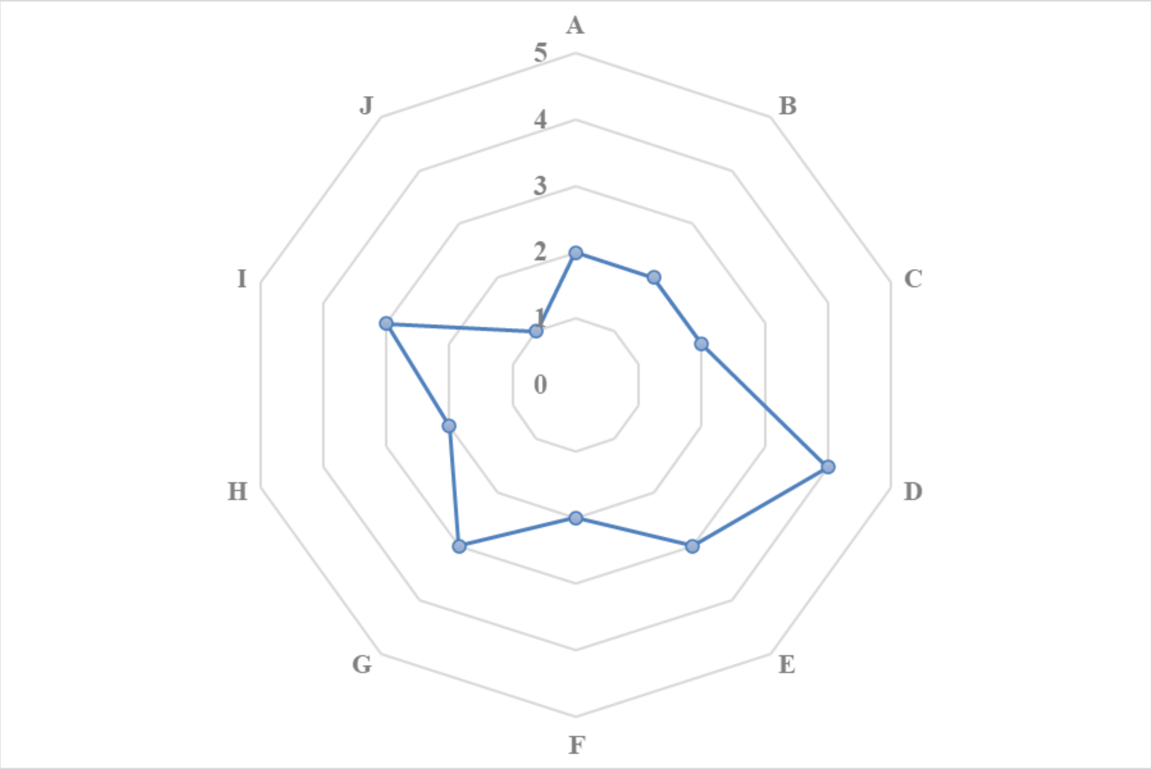

Figure 37: Building Block 4 and Associated Dimensions

Approximately 50% of investigated Greenhouses are at the "Basic Level," where humans execute Greenhouse processes with the assistance of basic automation, as shown by the survey results in figure 38.

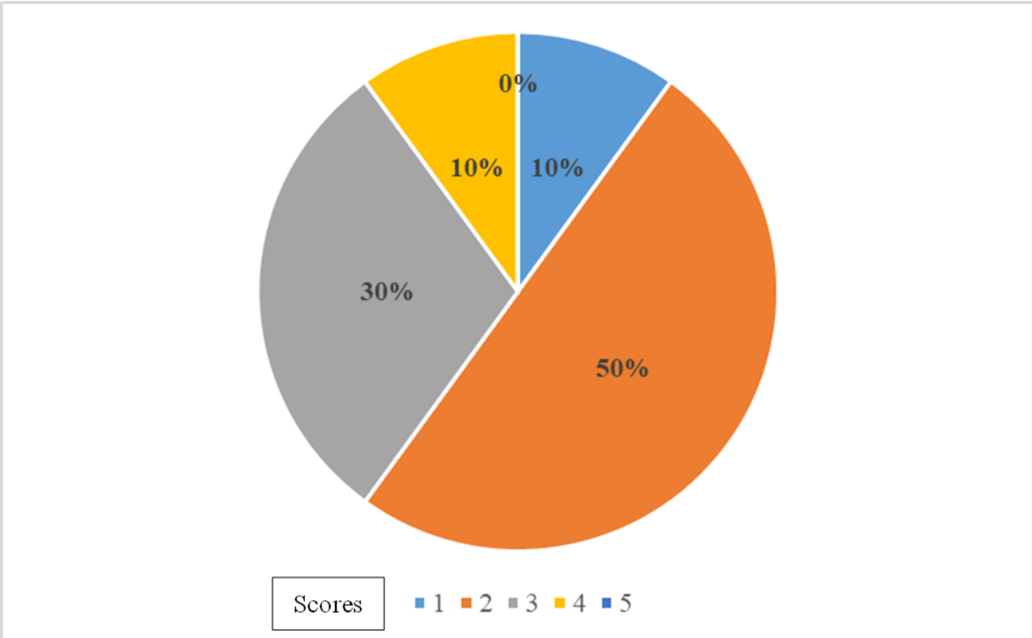

Figure 38: Responses to the Dimension 10 Questions

The technologies they are currently using include spray robots, ERP systems, Priva systems, automated packaging and labeling, and automated climate and irrigation.

The author believes that when a Greenhouse has matured enough in its processes to require more advanced technologies for further development, more technologies should be adopted. This should happen when the aim of employing these technologies is defined; clearly, the infrastructure is in place, and when the Greenhouses have attained this level of process maturity. If not, using advanced technologies will result in higher costs for Greenhouses. How can advanced technologies assist them? For instance, when their processes have not yet been established, they have not yet been standardized, personnel are not taught the necessary skills and knowledge, they are not aware of their Greenhouse risks and do not know how to manage them, etc. As a result, in the following stage, the dimensions of the Greenhouses should be prioritized based on their building block and dimensions analysis and corresponding maturity level. Then an improvement strategy should be established for the highest priority ones.

4.3.3. Prioritizing Dimensions and Providing Implementation Strategy

The primary goal of this study is to assist Greenhouses in identifying their existing advanced technology maturity that can support their processes and assess whether their Greenhouse is capable or developed enough to deploy the digital twin-Value stream.

According to the analysis performed on the various Greenhouses' data, 90% of the studied Greenhouses had "basic" or "intermediate" maturity levels, indicating that they have not yet reached the level of maturity needed to deploy DT-VS. They should therefore upgrade their Greenhouses in a range of aspects to get them ready for the adoption of cutting-edge technology and to facilitate the deployment of DT-VS.

Table 27 presents the average score of each dimension among all selected Greenhouses, the minimum acceptable maturity level at which new technologies can be adopted, and the existing gap between the current state and the desired state. Based on the knowledge acquired via many research and experiences in this field, the author specifies the desired state in this study. Then, an improvement strategy, table 28, will be developed to bring those dimensions up to the expected maturity level.

Based on the data analysis, on average, the technology capability dimension received the lowest score, 2.40 ~ 2, among the various dimensions, which means humans execute Greenhouse processes with the assistance of basic automation, as could be predicted from earlier analyses. However, before we focus on upgrading this dimension, we must check whether other dimensions are developed enough and whether the requirements for technology adoption have been satisfied to ensure that adopting new technologies is effective and beneficial for the Greenhouse. According to the findings, the top significant gaps are related to dimensions 6, 3, and 5, respectively. Thus, before investing any funds to employ new technologies, we must ensure that these dimensions have achieved the desired level.

Table 27: Gap Analysis in Greenhouse Sector

Building Block	Dimension Number	Dimension Name	Current Dimension Score on Average	Minimum Acceptable	Gap
Business Structure Assessment	1	Vision	2.70	3.00	0.30
	2	Culture	3.80	4.00	0.20
	3	Risk Management Approach	2.90	4.00	**1.10**
	4	Decision-Making Approach	4.00	4.00	0.00
Processes Assessment	5	Production Processes	3.00	3.80	**0.80**
	6	Crop Protection Processes	2.90	4.30	**1.40**
	7	Value Chain Processes	2.90	3.50	0.60
	8	Process Integration	2.60	2.00	(0.60)
People Assessment	9	Skills & Competence	2.90	3.20	0.30
Technologies Assessment	10	Technology Capability	2.40	2.00	(0.40)

The following table, 28, summarizes the three highest priority dimensions' improvement plans proposed by the author. The Greenhouses should, however, adjust it according to their situation and, if necessary, seek extra resources and practical training.

Table 28: Improvement Strategies for Greenhouse Agriculture Sector

Dimension Number	Dimension Name	Strategies
6	Crop Protection Processes	1. Determine all crop protection processes that are specific to your Greenhouse. 2. Identify the connectivity between crop protection processes, main production processes, and Greenhouse conditions. 3. Develop Standard Operational Procedures (SOPs) for the crop's protection processes. 4. Ensure all required resources and facilities are in place, and your employees are trained to utilize/ apply them. 5. Develop the metrics for their success and efficiency assessment. 6. Visualize all processes for their transparency. 7. Plan your crop protection processes, considering the logical relation with other production processes and your Greenhouse condition. 8. Routinely monitor the processes execution, Greenhouse condition, and on-time delivery of materials like bios, chemicals, etc., and evaluate their effectiveness and adherence to SOPs. 9. Collect and record all data for further analysis.
3	Risk Management Approach	1. Identify all potential risks (e.g., **people risk** like shortage of human capital, lack of training and resource management, **process risk** like not adhering to the proper procedures, and **product risk** like the occurrence of pest infestation. 2. Asses the risks, calculate the risk score and prioritize them. 3. Treat the risks by developing preventive and proactive plans. 4. Always watch for risk problems. 5. Monitor and review the risks plan for any modifications. 6. Collect and record any data related to risks occurrence.

Dimension Number	Dimension Name	Strategies
5	Production Processes	1. Ensure all production processes specific to your Greenhouse are identified and there are Standard Operational Procedures (SOPs) for them. 2. Ensure all required resources and facilities are in place and your employees are trained to utilize/ apply them. 3. Develop the metrics for process success and efficiency assessment and visualize all processes for their transparency. 4. Plan your production processes and resources considering their logical sequence and scientific significance. 5. Routinely monitor the processes execution, Greenhouse condition, and on-time delivery of materials and evaluate their effectiveness and adherence to SOPs. 6. Collect and record all data for further analysis. 7. Try to apply some Lean manufacturing principles in your production processes to improve them.

Implementing these strategies can help Greenhouses where they suffer from insufficient maturity of these dimensions to improve them and bring them to the desire state. After improving top priority dimensions, based on DT-VS Implementation Strategy, figure 19, that already discussed in section 3.4 of this study, we reassess the maturity of our Greenhouse to determine the most recent level of maturity and determine which other dimensions still require development. We will also be actively looking for ways to enhance our Greenhouse's processes to increase productivity, quality, and revenue while lowering any risks that might have a negative impact on it.

Figure 19: DT-VS Implementation Strategy

CHAPTER 5- DISCUSSION AND CONCLUSION

Aside from its benefits, each study has a variety of challenges and limitations. The final chapter of this study includes the discussion, significance of the research, limitations, conclusions, and recommendation for future work.

5.1. Discussion

The thesis aimed to develop a maturity assessment model specifically for Greenhouse agriculture, which will aid Canadian Greenhouse farmers in determining the level of maturity of their processes and acquired technology and help them reach a strategic roadmap for adopting value stream mapping and digital twin for advanced Greenhouse process management. The proposed method in this study is a Maturity Assessment Model, which identifies important core dimensions in Greenhouses to be analyzed before moving forward with DT-VS development, a questionnaire to extract needed information, numerical equations to quantify the results for better analysis, and an assessment procedure to guide growers from the start point to reach a realization plan for the DT-VS employment. This specific-sector Maturity Assessment Model supports a successful transition from traditional Greenhouse farming management into real-time monitoring and intelligent decision-making.

Multiple use cases and case study (ten Greenhouses) were studied to validate the proposed maturity assessment model. The analyses of each building block and their corresponding dimensions were shared with Greenhouse participants, and they were asked a few questions regarding the evaluation of the results. They were first asked about their degree of satisfaction with the technology ecosystem that now exists in their Greenhouse and then about how they believed adopting more cutting-edge technologies could assist them in achieving their business objective. According to the data analysis, 60% of them think that their current technology ecosystem can support them in achieving their business goals in figure 39. About 70% believe that implementing more cutting-edge technology, like scouting drones, machine learning, and Digital Twin, than they currently use can significantly accelerate their progress toward those goals, figure 40.

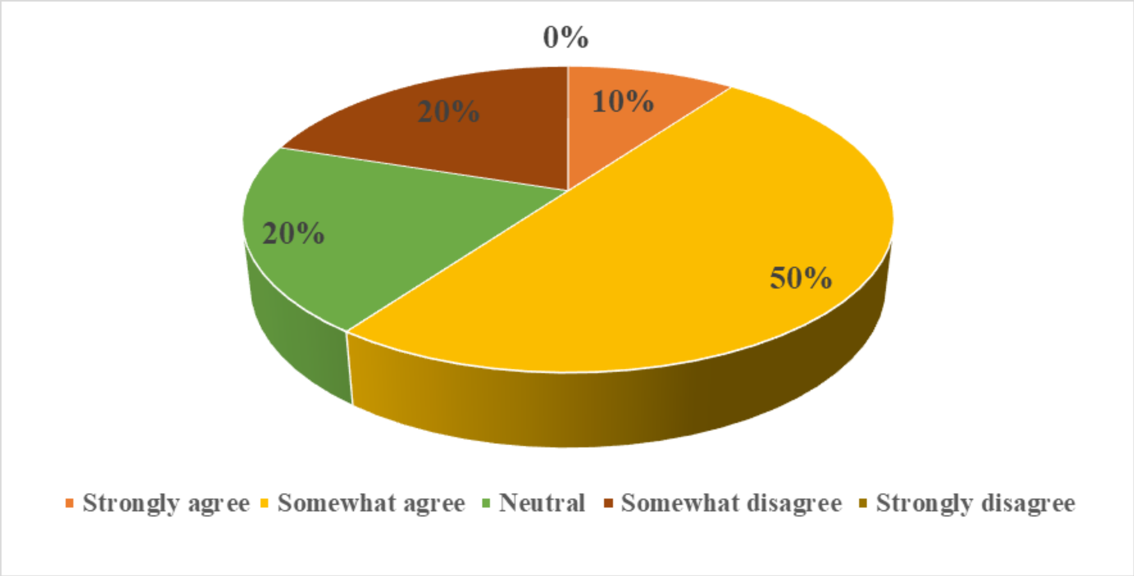

Figure 39: Satisfaction with Existing Technologies

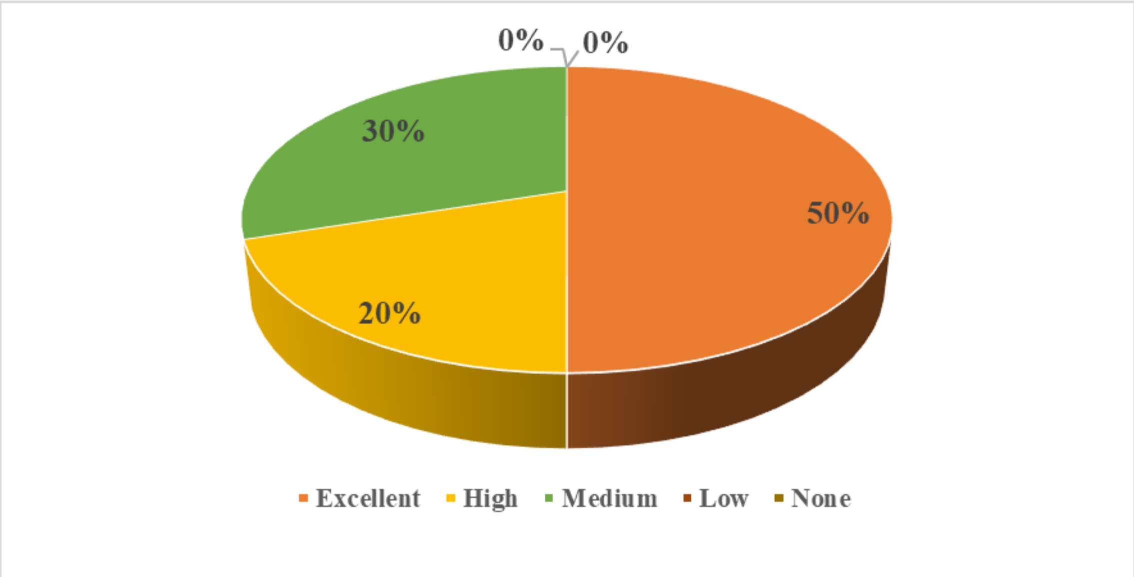

Figure 40: Additional Technological Adoption is Desired

They were then questioned about the effectiveness of the questionnaire and maturity assessment results in capturing the current maturity of their processes and whether this study could assist them in developing a strategy for transitioning from conventional Greenhouse agriculture to lean and smart Greenhouse agriculture. Findings show that about 60% of the selected Greenhouses strongly agree with the research results, and they believe that this study will be helpful to them for future improvement, figure 41. To determine whether there is a connection between crop size and respondents' satisfaction, another analysis of the closing questions by crop size was conducted, figures 42, 43, and 44. According to the findings, there is no significant relationship between those.

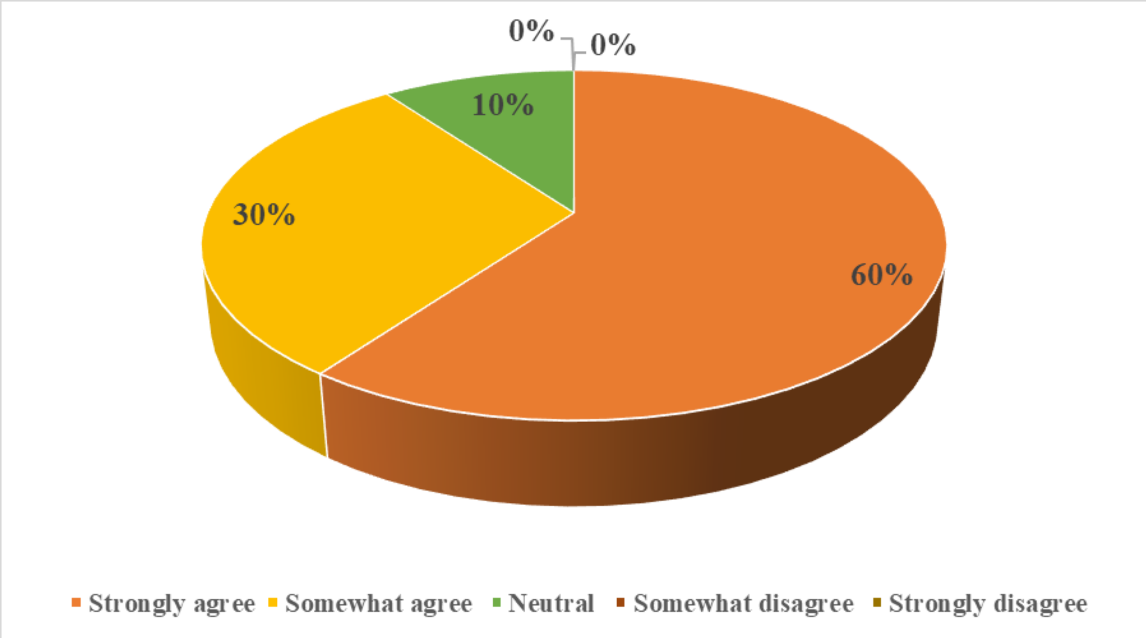

Figure 41: Satisfaction with the Significance of this Study.

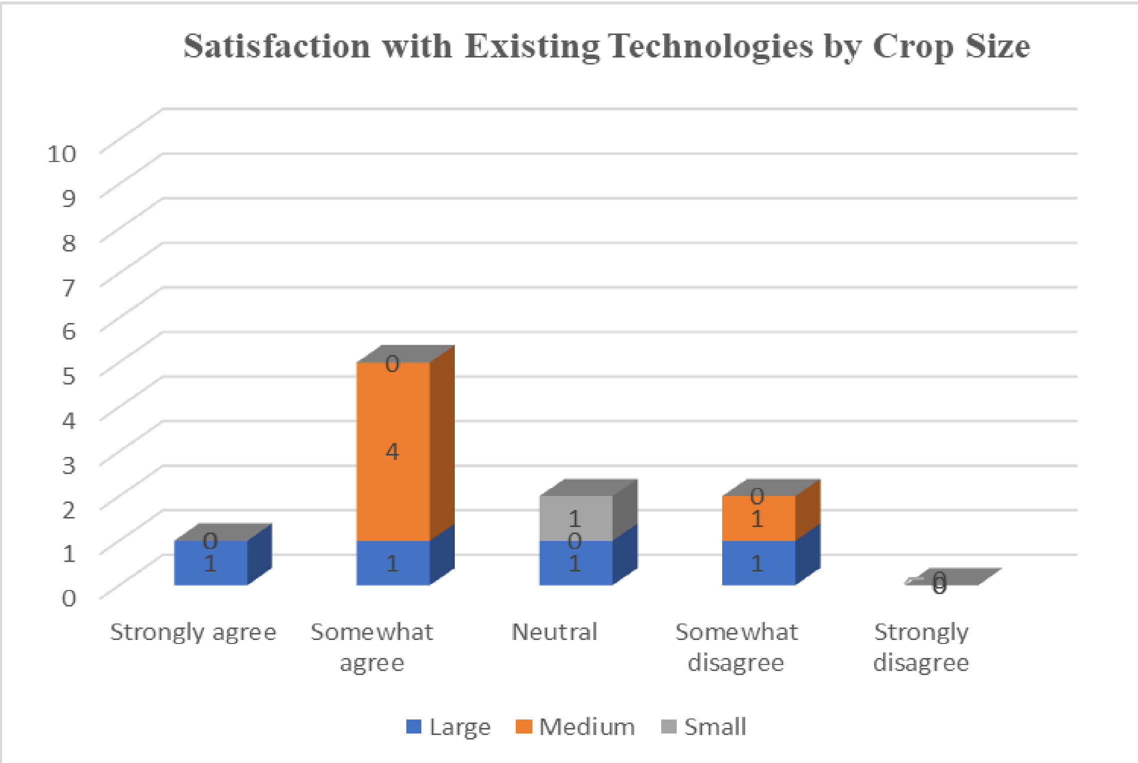

Figure 42: Satisfaction with Existing Technologies by Crop Size

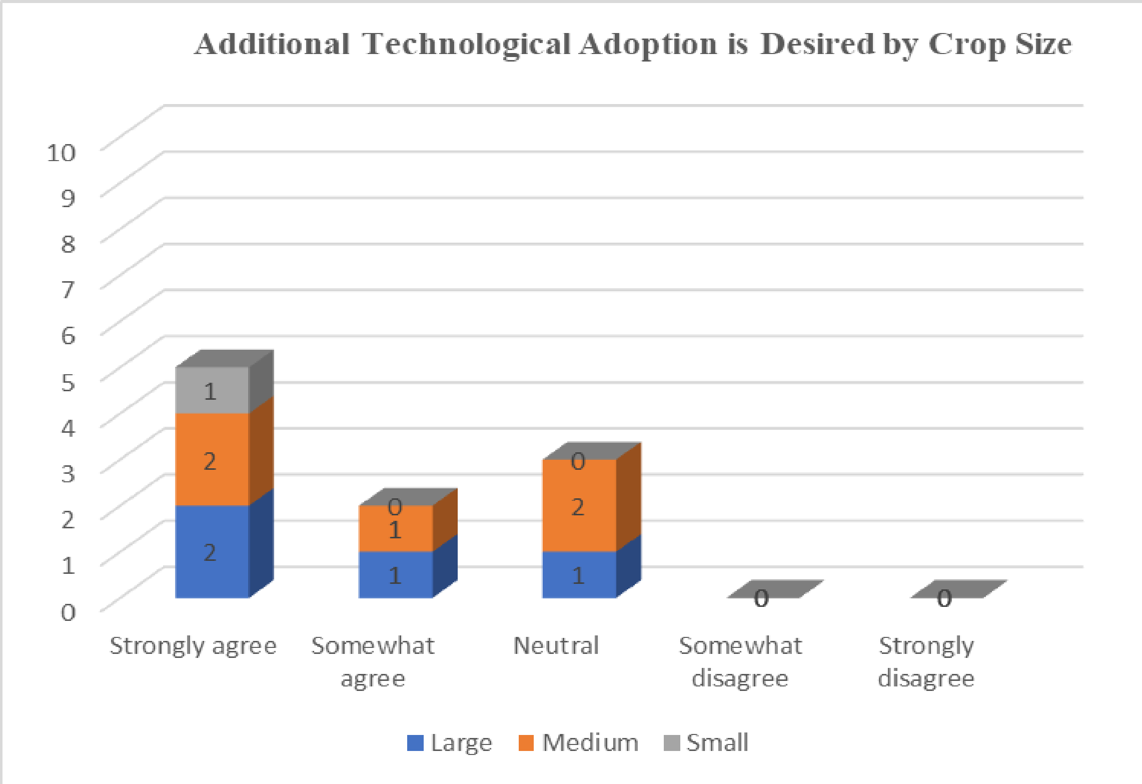

Figure 43: Additional Technological Adoption is Desired by Crop Size

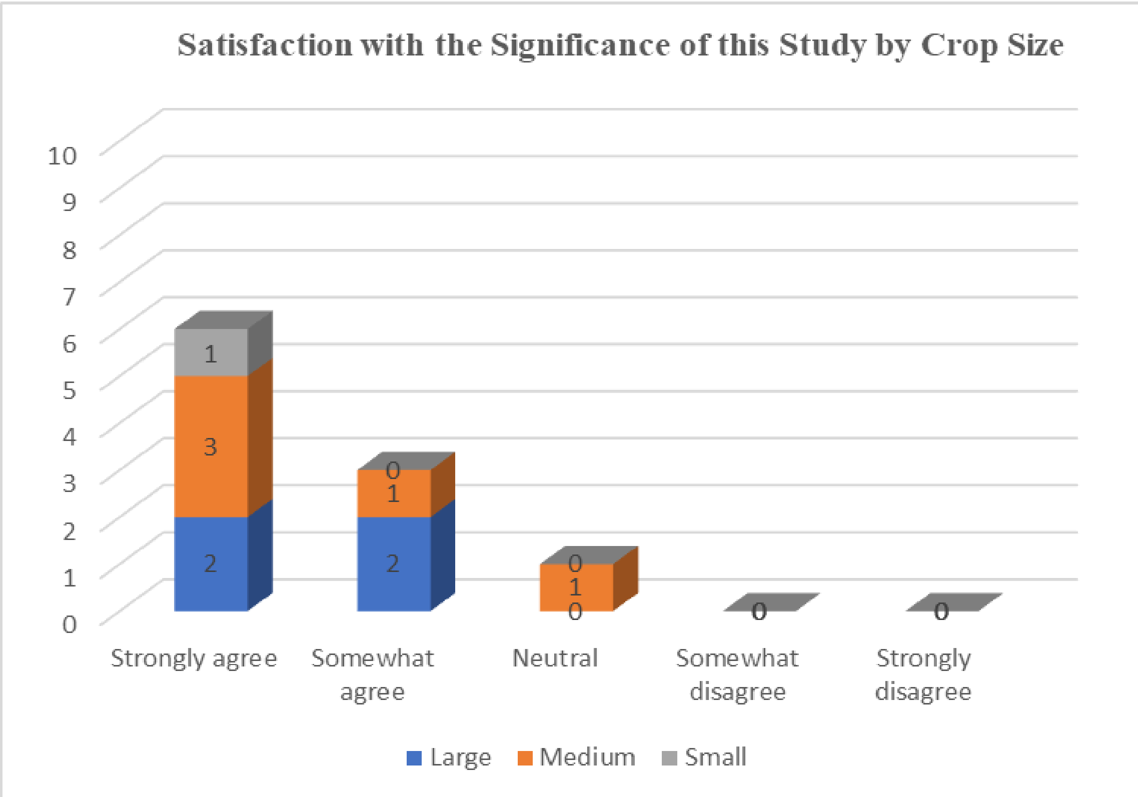

Figure 44: Satisfaction with the Significance of this Study by Crop Size

5.2. Significance

As noted in the research gap analysis, most papers about technology adoption in Greenhouse agriculture relate to environmental parameters like temperature, humidity, CO_2, irrigation, etc.

By establishing a sector-specific questionnaire, this study distinguishes itself from previous ones by focusing on Greenhouse agriculture processes and how technology adoption might help them.

Another advantage of this study is that it enables Greenhouses to evaluate the current maturity level of their processes and to compare their outcomes to those of other Greenhouses. Businesses typically dislike disclosing their state to outside parties. However, the study's questionnaire encourages Greenhouse involvement because of its anonymity aspect. Additionally, through the conversation with them, they learned about other prospects for process improvement that they needed to be made aware of, including Digital Twin, Industry 4.0, and Lean manufacturing principles and their capabilities.

5.3. Limitations

Every research has its limitations. Some of the study's limitations include the lack of sufficient reliable resources regarding the various processes of Greenhouse agriculture, its protection processes, mapping of its value chain, the lack of established standards for processes, and an insufficient level of familiarity with cutting-edge technologies and their applications. For instance, they were unfamiliar with the scientific terminology we used to describe concepts and technology. Still, it was obvious from their expression that they were already using such concepts and technologies.

The number of participants in this questionnaire was another limitation; many were not interested in taking part, or it was challenging to arrange a time to go over the questionnaire due to their hectic schedules. Therefore, the results of this study cannot be generalized due to the small sample size and the fact that the participants were from a particular area, so further samples should be evaluated in the future to support the findings.

5.4. Conclusion

The struggle to produce more products of higher quality while remaining profitable becomes more and more critical as the world's population grows. The agricultural sector benefits from Greenhouse farming since it allows plants to be grown all year round regardless of location, climate, and other environmental considerations. This will be accomplished, though, once they can effectively manage their resource constraints and production processes.

Traditional Greenhouse agriculture is significantly hampered by the absence of adequate and accurate data, and producers rely daily decisions on costs rather than the industry standard. According to a literature study of recent publications, an emerging technology called Digital Twin-Value Stream (DT-VS) can benefit this sector by providing decision-makers with a more thorough understanding of their processes by using a Digital Twin at the value stream level. However, knowing where they stand is a precondition for choosing future activities to deploy such technologies in Greenhouses.

The goal of this study was to develop a model for maturity assessment that would capture the current capabilities of Greenhouses with regard to the maturity level of their processes and technology adoption for supporting them and assessing whether they are ready to embrace intelligent technologies to optimize their processes and improve their managerial and daily decision-making. After that, based on the findings, assist agricultural producers in creating their strategic roadmap for utilizing new technologies, like Digital Twin- Value Stream, to enhance Greenhouse process management.

This study used a sample of 10 (ten) Greenhouses to evaluate the maturity of Greenhouse agriculture processes from various perspectives using a questionnaire tailored to this industry. Production processes, crop protection processes, enabling technology, and staff readiness for changes are a few examples of these dimensions.

Based on the assumption that all ten dimensions are equally significant, the overall maturity of the Greenhouse agriculture sector was calculated in this study. Based on the average of all ten sample greenhouses' overall maturity scores, the greenhouse agriculture sector, within the scope of this research, has a maturity level score of three, and the maturity level corresponding to that number is intermediate.

According to the analysis performed on the ten greenhouses' data, 90% of the studied greenhouses had "basic" or "intermediate" maturity levels, indicating that they have not yet reached the level of maturity needed to deploy DT-VS. They should therefore upgrade their Greenhouses in a range of aspects to get them ready for the adoption of cutting-edge technology and to facilitate the deployment of DT-VS. Then, participants in the Greenhouse were informed of the analyses of each building block and its associated dimensions. The efficiency of the questionnaire and maturity assessment results in capturing the current maturity of their processes was then discussed with them. Approximately 60% of the chosen Greenhouses highly agreed with the findings and their applicability, and they highlighted that this study would benefit them for future improvement.

In the end, Greenhouse agriculture, value stream mapping, digital twins, and the maturity assessment model are among the main topics covered in this study, and linkages between them are summarized in Figure 45.

5.5. Recommendations for Future Work

This study can be expanded to various greenhouses in different geographic locations to compare the results. All building blocks and dimensions are given the same weight in this study, and the inference prioritizing method utilized in the maturity assessment analysis was assumed to apply to all studied cases. Future work may adopt approaches, like the Analytic Hierarchy Process (AHP) or Pugh Matrix, that can account for various factors, such as primary processes should be given more weight than supplementary processes, or certain maturation levels should be given more weight than others, as they can significantly alter greenhouse management.

Some other potential areas for further research or improvement could include evaluating the effectiveness of the method over a long period of time and comparing the proposed method with other existing methods. The thesis focuses on the greenhouse farming sector, it could be interesting to see how this model can be adapted and applied to other sectors. The outcomes of a few case studies are described in the thesis; however, it is unclear how well the strategy is scalable to bigger and more intricate greenhouse operations. The scalability of the method can be the subject of future study. The thesis offers a framework for assessment that greenhouse farmers can use to identify gaps and create a strategic roadmap for the use of digital twin technology, but it omits any discussion of the cost-benefit analysis of this adoption. The cost-benefit analysis of the suggested approach could be interesting to investigate.

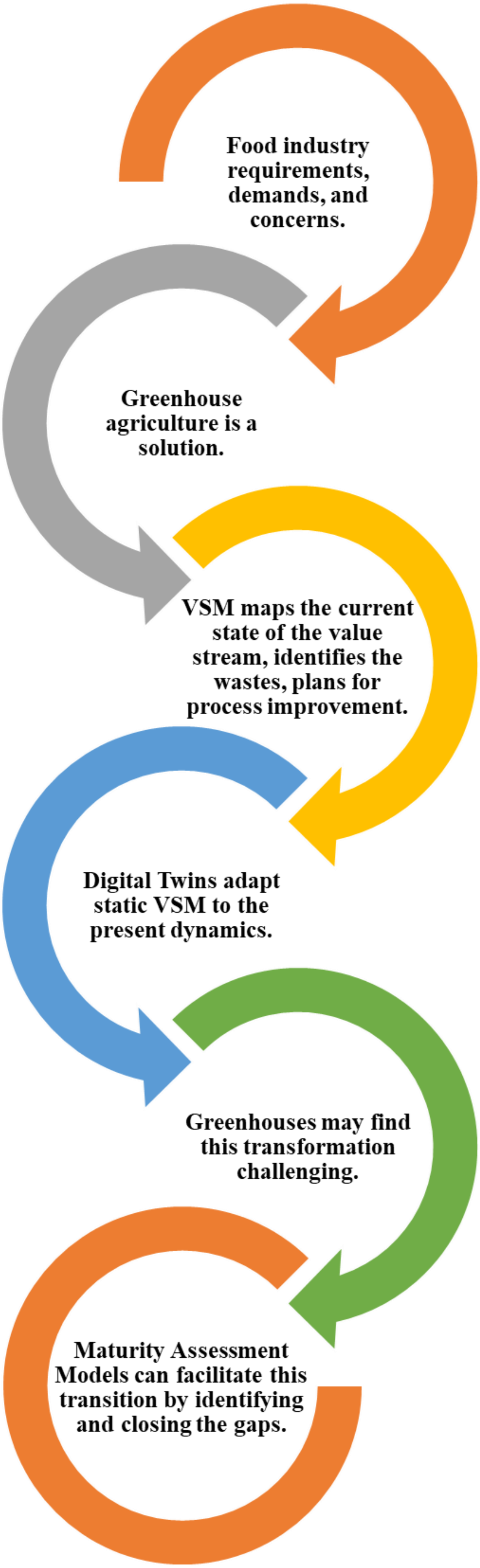

Figure 45: Origin of Need for Developing DT- VSM

REFERENCES/ BIBLIOGRAPHY

Abou Tabl, A., Alkhateeb, A. and ElMaraghy, W. (2021) 'Deep Learning Method based on Big Data for Defects Detection in Manufacturing Systems Industry 4.0', International Journal of Industry and Sustainable Development, 2(1), pp. 1–14. Available at: https://doi.org/10.21608/ijisd.2021.145552.

Anonym (2022) Overview of Canada's agriculture and agri-food sector, Government of Canada. Available at: https://agriculture.canada.ca/en/canadas-agriculture-sectors/overview-canadas-agriculture-and-agri-food-sector (Accessed: 25 August 2022).

Anonym (no date) Integrated Pest Management, the Government of British Columbia. Available at: https://www2.gov.bc.ca/gov/content/industry/agriculture-seafood/animals-and-crops/plant-health/integrated-pest-management#:~:text=Integrated%20Pest%20Management%20is%20a,and%20in%20the%20home%20garden. (Accessed: 25 August 2022).

Ariesen-Verschuur, N., Verdouw, C. and Tekinerdogan, B. (2022) 'Digital Twins in greenhouse horticulture: A review', Computers and Electronics in Agriculture, 199, p. 107183. Available at: https://doi.org/10.1016/j.compag.2022.107183.

Asdecker, B. and Felch, V. (2018) 'Development of an Industry 4.0 maturity model for the delivery process in supply chains', Journal of Modelling in Management, 13(4), pp. 840–883. Available at: https://doi.org/10.1108/JM2-03-2018-0042.

Assad Neto, A. et al. (2020) 'Digital twins in manufacturing: An assessment of key features', in Procedia CIRP. Elsevier B.V., pp. 178–183. Available at: https://doi.org/10.1016/j.procir.2020.05.222.

Azevedo, A. and Santiago, S.B. (2019) 'Design of an Assessment Industry 4.0 Maturity Model: an application to manufacturing company', International Conference on Industrial Engineering and Operations Management [Preprint].

Bandara, O.K.K., Tharaka, V.K. and Wickramarachchi, A.P.R. (2019) Industry 4.0 maturity assessment of the Banking Sector of Sri Lanka; Industry 4.0 maturity assessment of the Banking Sector of Sri Lanka.

Barricelli, B.R., Casiraghi, E. and Fogli, D. (2019) 'A survey on digital twin: Definitions, characteristics, applications, and design implications', IEEE Access. Institute of Electrical and Electronics Engineers Inc. Available at: https://doi.org/10.1109/ACCESS.2019.2953499.

Bhatia, V., Kumawat, S. and Jaglan, V. (2022) 'Overview of the Role of the Internet of Things and Cyber-Physical Systems in Various Applications', in A.K. Tyagi and N. Sreenath (eds) Handbook of Research of Internet of Things and Cyber-Physical Systems. FIRST. Apple Academic Press Inc., pp. 3–10.

Botín-Sanabria, D.M. et al. (2022) 'Digital Twin Technology Challenges and Applications: A Comprehensive Review', Remote Sensing. MDPI. Available at: https://doi.org/10.3390/rs14061335.

Bucourt, M. de et al. (2011) 'Lean manufacturing and Toyota Production System terminology applied to the procurement of vascular stents in interventional radiology', Insights into Imaging, 2(4), pp. 415–423. Available at: https://doi.org/10.1007/s13244-011-0097-0.

Caiado, R.G.G. et al. (2021) 'A fuzzy rule-based industry 4.0 maturity model for operations and supply chain management', International Journal of Production Economics, 231. Available at: https://doi.org/10.1016/j.ijpe.2020.107883.

Chaplin, J.C., Martinez-Arellano, G. and Mazzoleni, A. (2020) 'Digital Twins and Intelligent Decision Making', in J.C. Chaplin, C. Pagano, and S. Fort (eds) DIGITAL MANUFACTURING FOR SMEs- An Introduction. Digital Manufacturing Training, pp. 159–186.

Chaux, J.D., Sanchez-Londono, D. and Barbieri, G. (2021) 'A digital twin architecture to optimize productivity within controlled environment agriculture', Applied Sciences (Switzerland), 11(19). Available at: https://doi.org/10.3390/app11198875.

Coulibaly, S. et al. (2022) 'Deep learning for precision agriculture: A bibliometric analysis', Intelligent Systems with Applications, 16, p. 200102. Available at: https://doi.org/10.1016/j.iswa.2022.200102.

Dittrich, M.A. et al. (2020) 'Shifting value stream patterns along the product lifecycle with digital twins', in Procedia CIRP. Elsevier B.V., pp. 3–11. Available at: https://doi.org/10.1016/j.procir.2020.01.049.

Dora, M., Lambrecht, E. and Gellynck, X. (2015) 'Lean Manufacturing to Lean Agriculture: It's about time', in Industrial and Systems Engineering Research Conference. Proceedings (p. 633). Institute of Industrial and Systems Engineers (IISE

ElMaraghy, H. et al. (2021) 'Evolution and future of manufacturing systems', CIRP Annals, 70(2), pp. 635–658. Available at: https://doi.org/10.1016/j.cirp.2021.05.008.

ElMaraghy, H. and ElMaraghy, W. (2022) 'Adaptive Cognitive Manufacturing System (ACMS)–a new paradigm', International Journal of Production Research, pp.1-14. Available at: https://doi.org/10.1080/00207543.2022.2078248.

ElMaraghy, W. (2021) 'Engineering Design Methodology and Applications (EDMA)', Engineering Course Lecture. University of Windsor, Canada. (Private Communication).

Fatima, K. et al. (2023) ‘Digital Twin Greenhouse Technologies for Commercial Farmers’, in The 1st International Precision Agriculture Pakistan Conference 2022 (PAPC 2022) & mdash; Change the Culture of Agriculture. Basel Switzerland: MDPI, p. 33. Available at: https://doi.org/10.3390/environsciproc2022023033.

Fei Tao, Meng Zhang and A.Y.C. Nee (2019) ‘Five-Dimension Digital Twin Modeling and Its Key Technologies’, in Digital Twin Driven Smart Manufacturing. Academic Press is an imprint of Elsevier, pp. 49–87.

Fenton, B. (2022) Human-Machine Collaboration in Healthcare Innovation. Master dissertation, University of Windsor, Canada. Available at: https://www.proquest.com/docview/2666592909?parentSessionId=ZcyBxSdK7bLhLoy2Clyw1BBcwmPD%2FD8sogHowus0sQs%3D&pq-origsite=primo&accountid=14789 (Accessed: 27 November 2022).

Forno, A.J.D. et al. (2014) ‘Value stream mapping: A study about the problems and challenges found in the literature from the past 15 years about application of Lean tools’, International Journal of Advanced Manufacturing Technology, 72(5–8), pp. 779–790. Available at: https://doi.org/10.1007/s00170-014-5712-z.

Frick, N. and Metternich, J. (2022) ‘The Digital Value Stream Twin’, Systems, 10(4), p. 102. Available at: https://doi.org/10.3390/systems10040102.

Ghobakhloo, M. (2018) ‘The future of manufacturing industry: a strategic roadmap toward Industry 4.0’, Journal of Manufacturing Technology Management, 29(6), pp. 910–936. Available at: https://doi.org/10.1108/JMTM-02-2018-0057.

Guo, J. and Lv, Z. (2022) ‘Application of Digital Twins in multiple fields’, Multimedia Tools and Applications. Available at: https://doi.org/10.1007/s11042-022-12536-5.

Holopainen, M. et al. (2021) ‘The digital twin combined with real-time performance measurement in lean manufacturing’, in Real-time Simulation for Sustainable Production: Enhancing User Experience and Creating Business Value. Taylor and Francis Inc., pp. 1–242. Available at: https://doi.org/10.4324/9781003054214.

Howard, D.A. et al. (2020) ‘Data Architecture for Digital Twin of Commercial Greenhouse Production’, 2020 RIVF International Conference on Computing and Communication Technologies (RIVF).

Howard, D.A. et al. (2021) ‘Greenhouse industry 4.0 – digital twin technology for commercial greenhouses’, Energy Informatics, 4. Available at: https://doi.org/10.1186/s42162-021-00161-9.

Jiang, J.A. et al. (2013) ‘Application of a web-based remote agro-ecological monitoring system for observing spatial distribution and dynamics of Bactrocera dorsalis in fruit orchards’, Precision Agriculture, 14(3), pp. 323–342. Available at: https://doi.org/10.1007/s11119-012-9298-x.

Knibbe, W.J. et al. (2022) ‘Digital twins in the green life sciences’, NJAS: Impact in Agricultural and Life Sciences, 94(1), pp. 249–279. Available at: https://doi.org/10.1080/27685241.2022.2150571.

Kumar, S. and Singh, A. (2015) ‘Biopesticides: Present Status and the Future Prospects’, Journal of Biofertilizers & Biopesticides, 06(02). Available at: https://doi.org/10.4172/jbfbp.1000e129.

Leng, P. et al. (2011) ‘Applications and development trends in biopesticides’, African Journal of Biotechnology, pp. 19864–19873. Available at: https://doi.org/10.5897/AJBX11.009.

Lie, S.R. and Kusumastuti, R.D. (2021) ‘Process improvement using value stream mapping and lean methodology: a case study application in batch chemical process industry’, IOP Conference Series: Materials Science and Engineering, 1072(1), p. 012015. Available at: https://doi.org/10.1088/1757-899x/1072/1/012015.

Lu, Y., Liu, Z. and Min, Q. (2021) ‘A digital twin-enabled value stream mapping approach for production process reengineering in SMEs’, International Journal of Computer Integrated Manufacturing, 34(7–8), pp. 764–782. Available at: https://doi.org/10.1080/0951192X.2021.1872099.

Ma, K. et al. (2021) ‘Fine-grained pests recognition based on truncated probability fusion network via internet of things in forestry and agricultural scenes’, Algorithms, 14(10). Available at: https://doi.org/10.3390/a14100290.

Nasirahmadi, A. and Hensel, O. (2022) ‘Toward the Next Generation of Digitalization in Agriculture Based on Digital Twin Paradigm’, Sensors. MDPI. Available at: https://doi.org/10.3390/s22020498.

Pahl, G. et al. (2007) Engineering Design A Systematic Approach. 3rd edn. Springer.

Pekarcíková, M. et al. (2021) ‘Modelling and simulation the value stream mapping - case study’, Management and Production Engineering Review, 12(2), pp. 107–114. Available at: https://doi.org/10.24425/mper.2021.137683.

Pylianidis, C., Osinga, S. and Athanasiadis, I.N. (2021) ‘Introducing digital twins to agriculture’, Computers and Electronics in Agriculture, 184. Available at: https://doi.org/10.1016/j.compag.2020.105942.

Qi, Q. et al. (2021) ‘Enabling technologies and tools for digital twin’, Journal of Manufacturing Systems, 58, pp. 3–21. Available at: https://doi.org/10.1016/j.jmsy.2019.10.001.

Rafael, L.D. et al. (2020) ‘An Industry 4.0 maturity model for machine tool companies’, Technological Forecasting and Social Change, 159. Available at: https://doi.org/10.1016/j.techfore.2020.120203.

Rasheed, A., San, O. and Kvamsdal, T. (2020) ‘Digital twin: Values, challenges and enablers from a modeling perspective’, IEEE Access, 8, pp. 21980–22012. Available at: https://doi.org/10.1109/ACCESS.2020.2970143.

Ronaghi, M.H. (2021) ‘A blockchain maturity model in agricultural supply chain’, Information Processing in Agriculture. China Agricultural University, pp. 398–408. Available at: https://doi.org/10.1016/j.inpa.2020.10.004.

Salvadorinho, J. and Teixeira, L. (2021) ‘Stories told by publications about the relationship between industry 4.0 and lean: Systematic literature review and future research agenda’, Publications. MDPI AG. Available at: https://doi.org/10.3390/publications9030029.

Santos, R.C. and Martinho, J.L. (2020) ‘An Industry 4.0 maturity model proposal’, Journal of Manufacturing Technology Management, 31(5), pp. 1023–1043. Available at: https://doi.org/10.1108/JMTM-09-2018-0284.

Saraswat, P. et al. (2014) ‘A Review on Waste Reduction through Value Stream Mapping Analysis’, International Journal of Research (IJR), 1(6).

Schumacher, A., Nemeth, T. and Sihn, W. (2019) ‘Roadmapping towards industrial digitalization based on an Industry 4.0 maturity model for manufacturing enterprises’, in Procedia CIRP. Elsevier B.V., pp. 409–414. Available at: https://doi.org/10.1016/j.procir.2019.02.110.

Shao, G. and Helu, M. (2020) ‘Framework for a digital twin in manufacturing: Scope and requirements’, Manufacturing Letters, 24, pp. 105–107. Available at: https://doi.org/10.1016/j.mfglet.2020.04.004.

Skobelev, P. et al. (2021) ‘Digital twin of rice as a decision-making service for precise farming, based on environmental datasets from the fields’, in Proceedings of ITNT 2021 - 7th IEEE International Conference on Information Technology and Nanotechnology. Institute of Electrical and Electronics Engineers Inc. Available at: https://doi.org/10.1109/ITNT52450.2021.9649038.

Sultan, S. and Khodabandehloo, A. (2020) Improvement of Value Stream Mapping and Internal Logistics through Digitalization: A study in the context of Industry 4.0. Master dissertation, Malardalen University, Sweden. Available at: http://mdh.diva-portal.org/smash/get/diva2:1437093/FULLTEXT01.pdf (Accessed: 18 August 2022).

Sun, J., Zhang, F. and Chen, Z. (2012) ‘The designment of digital greenhouse expert system’, in Applied Mechanics and Materials, pp. 199–204. Available at: https://doi.org/10.4028/www.scientific.net/AMM.190-191.199.

Sundar, R., Balaji, A.N. and Satheesh Kumar, R.M. (2014) ‘A review on lean manufacturing implementation techniques’, in Procedia Engineering. Elsevier Ltd, pp. 1875–1885. Available at: https://doi.org/10.1016/j.proeng.2014.12.341.

Tao, F. et al. (2019) ‘Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison’, Engineering, 5(4), pp. 653–661. Available at: https://doi.org/10.1016/j.eng.2019.01.014.

Tonelli, F. et al. (2016) ‘A Novel Methodology for Manufacturing Firms Value Modeling and Mapping to Improve Operational Performance in the Industry 4.0 Era’, in Procedia CIRP. Elsevier B.V., pp. 122–127. Available at: https://doi.org/10.1016/j.procir.2016.11.022.

Tran, T.A. et al. (2021) ‘Real-time locating system and digital twin in Lean 4.0’, in SACI 2021 - IEEE 15th International Symposium on Applied Computational Intelligence and Informatics, Proceedings. Institute of Electrical and Electronics Engineers Inc., pp. 369–374. Available at: https://doi.org/10.1109/SACI51354.2021.9465544.

Uhlemann, T.H.J. et al. (2017) ‘The Digital Twin: Demonstrating the Potential of Real Time Data Acquisition in Production Systems’, Procedia Manufacturing, 9, pp. 113–120. Available at: https://doi.org/10.1016/j.promfg.2017.04.043.

Uhlenkamp, J.-F. et al. (2022) ‘Digital Twins: A Maturity Model for Their Classification and Evaluation’, IEEE Access, 10, pp. 69605–69635. Available at: https://doi.org/10.1109/ACCESS.2022.3186353.

Verdouw, C. et al. (2021) ‘Digital twins in smart farming’, Agricultural Systems, 189. Available at: https://doi.org/10.1016/j.agsy.2020.103046.

Wagire, A.A. et al. (2021) ‘Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice’, Production Planning and Control, 32(8), pp. 603–622. Available at: https://doi.org/10.1080/09537287.2020.1744763.

Wollermann Umpierrez, A. (2020) ‘Maturity Assessment of Digital Twin Implementations in The Commercial Aerospace Industry’, 10th International Conference on Industrial Technology and Management (ICITM). Available at: https://doi.org/10.13140/RG.2.2.25925.17122.

Zoubek, M. et al. (2021) ‘Industry 4.0 maturity model assessing environmental attributes of manufacturing company’, Applied Sciences (Switzerland), 11(11). Available at: https://doi.org/10.3390/app11115151.

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